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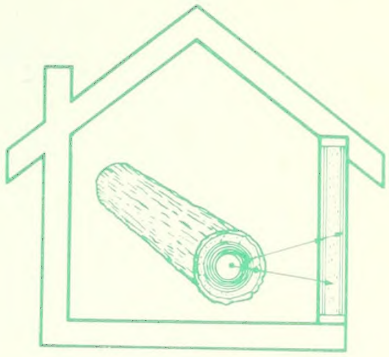

COM-PLY REPORT 1

THE COM-PLY RESEARCH PROJECT

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U.S. DEPARTMENT OF HOUSING AND URBAN DEVELOPMENT

NATIONAL FOREST SYSTEM COOPERATIVE FORESTRY FORESTRY RESEARCH
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COOPERATIVE RESEARCH

THE COM-PLY RESEARCH PROJECT

by

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Cooperative Research by

U.S. Department of Agriculture, Forest Service

Southeastern Forest Experiment Station

and

U.S. Department of Housing and Urban Development

Division of Energy, Building Technology

and Standards

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PREFACE

This report is one of a series on the possibilities of producing house framing and structural panels with particleboard cores and veneer facings. These COM-PLY or composite materials were designed to be used interchangeably with conventional lumber and plywood in homes. Research on structural framing is presently limited to COM-PLY studs but will be extended to include larger members such as floor joists.

In 1973, the home-building industry faced a shortage of lumber and plywood and consequent rising prices. Both industry and government recognized that this situation was not a temporary problem, and that long-range plans for better using the Nation's available forest resources would be necessary to solve the problem.

The USDA Forest Service and the U.S. Department of Housing and Urban Development accelerated cooperative research on ways to utilize the whole tree. They concentrated on composite wood products made with particleboard and veneer as a way of using not only more of the tree stem, but also using less desirable trees and a greater variety of tree species than would conventional wood products. The particleboard which comprises a large portion of the COM-PLY stud is made from ground-up wood that comes from forest residues, mill residues, or low-quality timber. Thus, such composites could greatly increase the amount of lumber and plywood available for residential construction, our major use of wood, without eroding the Nation's timber supply.

Research on composite wall framing was performed by the Wood Products Research Unit, Southeastern Forest Experiment Station, Athens, Georgia. The American Plywood Association cooperated in these studies by designing and testing composite panel products that are interchangeable with plywood. Both types of products have been incorporated in demonstration houses.

Included in this series will be reports on structural properties, durability, dimensional stability, strength, and stiffness of composite studs. Other reports will describe the overall project, compare the strength of composite and solid wood studs, suggest performance standards for composite studs, and provide construction details on houses incorporating such studs. Still others will explore the economic feasibility of manufacturing composite studs and panels and estimate the amount and quality of veneer available from southern pines. These reports, called the COM-PLY series, will be available from the Southeastern Forest Experiment Station and the U.S. Department of Housing and Urban Development.

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THE COM-PLY RESEARCH PROJECT

Abstract.--This report describes the development of composite wood or COM-PLY products to be used as lumber and panels in light frame construction. Composites combine veneer and particleboard in a manner that can more than double the yield of structural wood products from a single tree. The report describes demonstration houses built with composite lumber and panels made on production-line equipment. It also discusses how the new composite products will extend our forest resources and improve forest management.

KEYWORDS: Composite lumber, composite panels, particleboard, veneer, wood utilization, house framing, house sheathing, wood products.

As a result of America's lumber shortage in 1973, the Forest Service has intensified its programs in forest management and wood utilization. Not only has it reemphasized the planting and improving of trees and timber stands, but it is developing more efficient ways of harvesting timber and manufacturing wood products. Particular attention is being focused on ways to alleviate America's continuing housing shortage, for the housing industry traditionally consumes more of our timber supply than any other.

One such Forest Service program to use timber more efficiently in the manufacture of wood products for homes is the COM-PLY research project. This project has developed composite or COM-PLY wood products that are direct substitutes for conventional lumber and plywood in residential construction. The present paper describes the COM-PLY research project and its accomplishments, the composite products that have been developed, the economic feasibility of their manufacture, and future research in the program.

HOW AND WHY THE PROJECT ORIGINATED

TIMBER SUPPLY AND DEMAND

Federal law charges the Forest Service with making periodic, comprehensive surveys of our Nation's forest resources. Experts study these data to determine if present and future supplies of forest resources will meet America's needs. One such study, "Outlook for Timber in the United States" (USDA Forest Service 1973), identified the need for research like the COM-PLY project so that our Nation can better utilize its forest resources. The report clearly establishes that demands for lumber, plywood, wood pulp, and other forest products are increasing more rapidly than available timber supplies. Specifically, the writers project that the population of the United States will increase nearly 40 percent between 1970 and 2000; thus, 281 million people will exert demands for timber products by the end of this century.

The writers also predict that the gross national product will increase at an average of 4.0 percent annually, or 240 percent by the year 2000. Such an increase would mean greater demands for wood products used in shipping containers and packaging, paper goods, printed material such as books and magazines, and advertising materials.

The problem of increased demand is compounded because the number of trees grown each year is decreasing. Our commercial forests are shrinking at a rate of about 500,000 acres per year, while the demands for forest products and lands for recreation, water, and wildlife are multiplying rapidly. In the Western United States, removals already exceed growth of new trees.

One of the greatest concerns engendered by an increasing population is the need for more housing. Already, the housing industry consumes 40 to 50 percent of our harvested timber each year (fig. 1). Shortages of timber for housing can only mean rising prices for timber products or substitution of nonwood products such as steel, aluminum, and plastics for home building.

Figure 1.--The different ways wood is consumed; based on 1970 data.

Certainly, no one wants to see higher prices for timber products, but the consequences of using nonwood building products must also be considered. This problem is discussed in the previously mentioned report by the USDA Forest Service (1973, p. 220):

> The air, water, and land pollution resulting from production of substitute materials such as steel, concrete products, and aluminum is of greater magnitude than in the case of timber products such as lumber and plywood.... Energy requirements and cost of processing competing materials are also much higher than for timber products.

Use of steel framing for exterior walls in residential construction, for example, is estimated to require over three times the amount of processing energy needed to produce lumber for the same job. For aluminum and concrete blocks, energy requirements are estimated to average more than eight times the requirement for lumber. Importing timber is not a solution to making up the deficit in our supply. Although the United States' net imports account for about 10 percent of the lumber it uses, rising prices and increased demand for timber in other countries make it impossible to solve our timber problem in this way. Furthermore, the United States would be hard pressed to balance her timber imports with comparable exports. Only by conserving and developing her own timber resources can this Country avoid placing herself in a vulnerable position similar to her plight during the oil shortage.

Eventually, we can increase our timber supply by accelerating tree planting, improving timber stands, and providing better protection of our forests from fire, insects, and disease. A more immediate answer is better utilization of our available timber. It is this goal--that of finding a more efficient way of utilizing timber--to which the COM-PLY research project is dedicated.

STRETCHING OUR TIMBER SUPPLY THROUGH BETTER UTILIZATION

If our timber supply is to be significantly increased by more efficient wood utilization, we must concentrate on groups of products and untapped timber resources that represent significant volumes of wood. One such group is the building products used by the construction industry. This industry consumes nearly two-thirds of the Nation's wood products in the form of lumber, plywood, and insulation board. As previously noted, residential construction and housing upkeep consume the major portion of these products. About 75 percent of the wood products consumed in home building are used for framing and sheathing (fig. 2). Thus, if wood could be used more efficiently in the manufacture of house framing and sheathing, there would be great potential for stretching the Nation's timber supply.

Our wood supplies could also be increased through better utilization of forest and mill residues. Despite recent progress in converting slabs, edgings, and veneer cores from sawmills and plywood plants into pulp and particleboard, unused plant residues still represent a sizable resource (fig. 3). In 1970, unused, chippable wood at primary manufacturing plants amounted to 0.4 billion cubic feet, and all plant residues totaled about one billion cubic feet (12.4 million cords).

Another source of unused wood fiber is the large quantity of logging residues left in the forest each year (fig. 4). This material is discarded because of the high costs of recovery and such problems as the difficulty of removing bark from limbs and fragments. In 1970, these residues included some 1.6 billion cubic feet of wood from sound trees, plus at least this much material from rough, rotten, and dead trees (a total of about 40 million cords). Much of this residue, including sound portions of dead and damaged trees, could be salvaged if an economically feasible way could be devised to process and utilize it.

Still another large reservoir of unused timber is held in our hardwood forests. Although some people may be surprised by the fact, the United States has 70 million

more acres of hardwood forests than of coniferous or softwood forests (fig. 5). Ninety percent of the Nation's hardwood forests are in the East, close to residential markets. In fact, our northern forests in the East are predominantly hardwood, and more than half the forest lands in the South are also stocked with these species. Despite this preponderance of hardwoods, however, lumber and plywood come mainly from softwoods, leaving our hardwood resources relatively untapped.

Figure 2.--A house frame with part of the sheathing applied.

Thus, one possible way to stretch our timber supply is to devise building products that incorporate these various untapped resources. Such products would have the greatest effect if they could

-be used for house framing and sheathing

-incorporate forest and mill residues

-utilize some of our abundant hardwood supply

-be produced with conventional manufacturing equipment.

It was to develop such products that the COM-PLY research program was initiated. The products devised, which are intended for use as lumber and paneling in residential construction, are composites of solid and reconstituted wood.

Figure 3.--Trimmings and residue from sawing logs in a mill.

INITIATING THE COM-PLY RESEARCH PROJECT

The cooperative research project to develop composite lumber and panels stemmed from meetings of the USDA Forest Service, the Department of Housing and Urban Development, and the American Plywood Association in 1972 and was jointly sponsored by these organizations. Under this program, the American Plywood Association (APA) in Tacoma, Washington, performed laboratory research on composite panels. The Wood Products Research Unit of the Southeastern Forest Experiment Station at Athens, Georgia, performed laboratory research on composite lumber made with particleboard cores and outer faces of veneer; it also studied the economic feasibility of manufacturing composite products.

Although many types and sizes of composite lumber are feasible, the Wood Products Research Unit began with efforts to develop composite 2 x 4 studs used to frame walls of houses. Its phase of the project was limited to 2 x 4 studs because available time, funds, and staff dictated that only one product could be thoroughly studied. It would have been wasteful to spend money on larger, more complicated structural members when the basic, fundamental properties could be studied on smaller ones.

Figure 4.--Logging residues left after harvesting timber.

Another reason for limiting the project was to provide convenience of manufacturing. When a new product is introduced, manufacturers prefer that it be limited to a single size and type, as is the case with wall studs. Multiple-inventory items that come in a variety of sizes and types require more complicated machinery for manufacturing, as well as more complex methods for distributing and marketing.

Another factor that influenced the decision was economics. The profit margin on a sawn 2 x 4 stud is small. Therefore, if a composite stud could be developed that would profitably compete with sawn lumber studs, a manufacturer would have greater incentive to consider making multiple-inventory products such as composite floor joists with larger profit margins.

COMPOSITE PRODUCTS

Composite products are not a new idea. The concept of making building materials with a particleboard core sandwiched between outer plies of wood has been used for many years. For example, manufacturers often make doors and furniture parts such as desk tops by bonding one or more layers of veneer onto each wide face of a particleboard panel (fig. 6). These formations are often referred to as structural sandwich constructions.

Figure 5.--Acreage of coniferous and hardwood forests in the continential United States.

In such constructions, the thin strips of wood, called facings, resist loads from the sides and top, and the thick composite core connects the facings so that the entire construction acts as a rigid unit. To a large extent, the characteristics of the facings determine the stiffness, strength, and dimensional stability of the construction. Thus, each type of wood product is used to its best advantage.

Composite constructions are an economical method of making lumber and panels. Only a small amount of expensive facing material is used with the relatively inexpensive core.

COMPOSITE LUMBER

One of the COM-PLY studs developed by the Wood Products Research Unit is shown in figure 7. About 80 percent of the stud is particleboard and 20 percent is veneer. Chipped-up wood forms the particleboard core, and two strips of 1/6-inch-thick southern pine veneer face each 1-1/2-inch edge of the core. Phenol and phenol-resorcinol adhesives bond the two veneer strips to each other and to the core.

Structural tests showed that COM-PLY studs with two 1/6-inch strips of southern pine veneer are considerably stronger and stiffer than required for house construction. Studs composed of 16 to 19 percent southern pine veneer are adequate for structural use. The exact amount of veneer depends to some extent on the species and quality of southern pine and on the strength characteristics of the core.

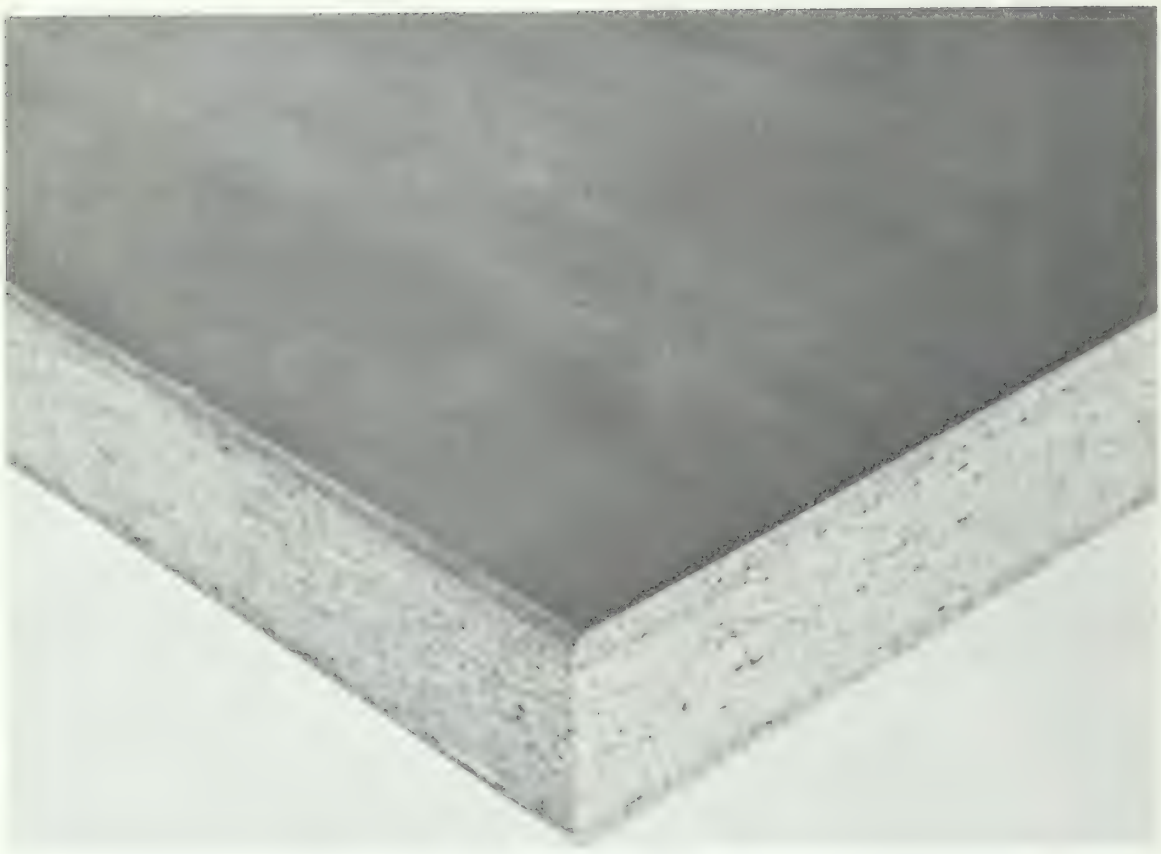

Figure 6.--Composite construction similar to that used in doors and desk tops.

Utilization

The COM-PLY concept represents a more efficient way of utilizing timber. This efficiency can best be understood by first examining the way logs are cut into conventional lumber at a sawmill.

With conventional methods, the lumber yield from a log varies widely, depending on the efficiency of the sawmill equipment. Some new equipment will produce yields over 50 percent, but our national average is between 30 and 40 percent (fig. 8). The 60 percent of the log that is not converted to lumber consists of bark, planer shavings, edgings and trimmings, and sawdust (fig. 9).

In the sawing process, some of the strongest, stiffest wood from the outer portion of the tree is turned into slabs and edgings, while the lower-quality wood from the center portion is used for lumber. Wood from the center portion is less dense, contains more knots and grain deviation, and cracks more readily during drying than wood from the outer portion. In other words, with conventional sawing the weakest portion of the tree is used for lumber and the strongest portion ends up as residues.

The COM-PLY concept takes the opposite approach. The high-strength, stiffer wood from the outer portion of the tree would be used for the veneer facings, and the lower-quality wood from the inner portion would be ground into particleboard for the core (fig. 10). An important point is that an average tree yields more

veneer than is needed to convert the tree completely into COM-PLY studs. Thus, the whole tree plus residues from other sources can be used in the end product.

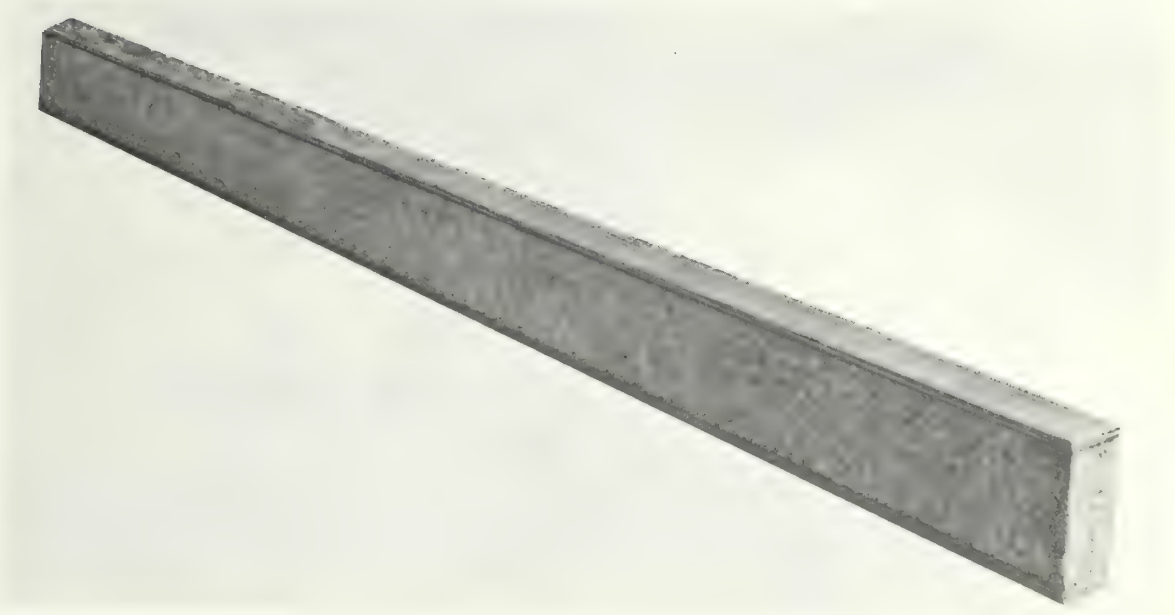

Figure 7.--A composite 2 x 4 stud.

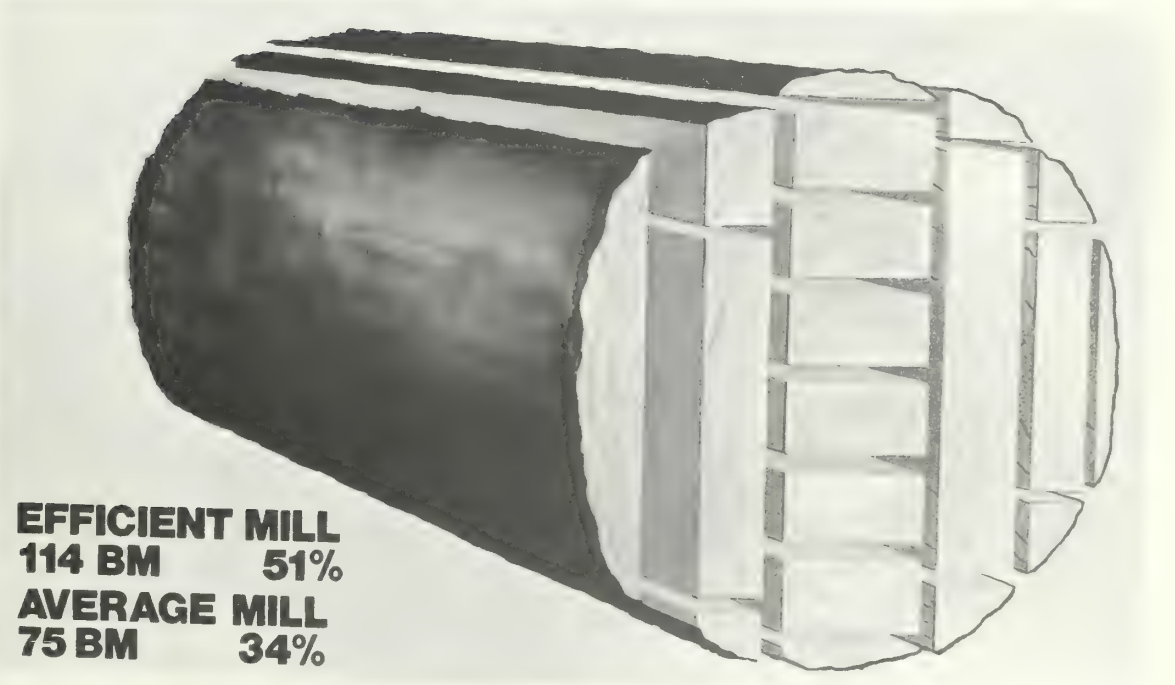

Figure 8.--Lumber yields at efficient and average sawmills. Percentages indicate utilization of small-diameter logs of typical length.

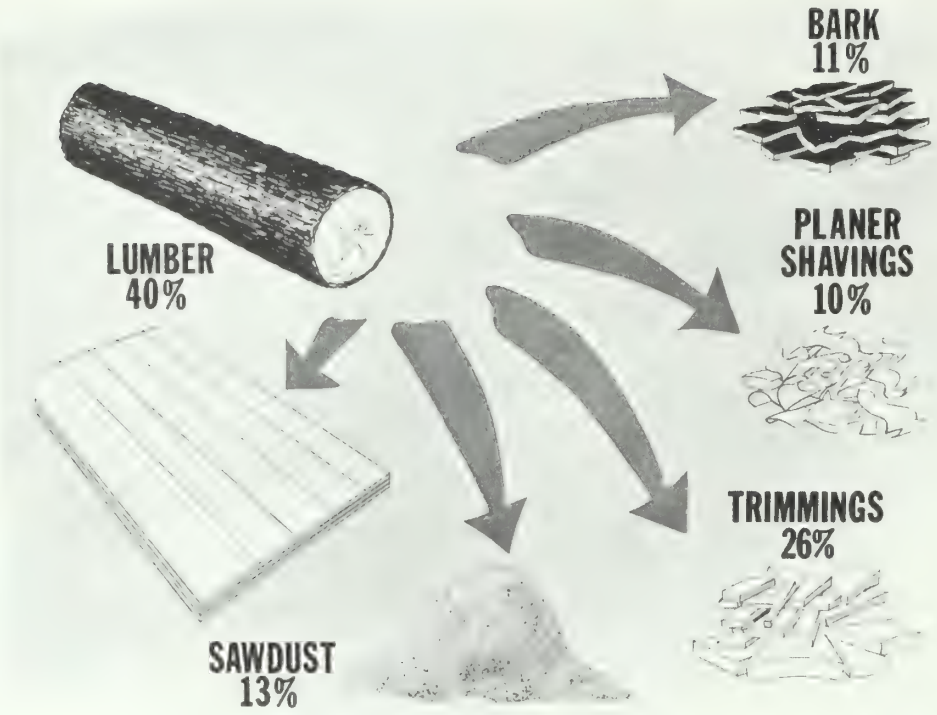

Figure 9.--Conversion of logs into sawn lumber.

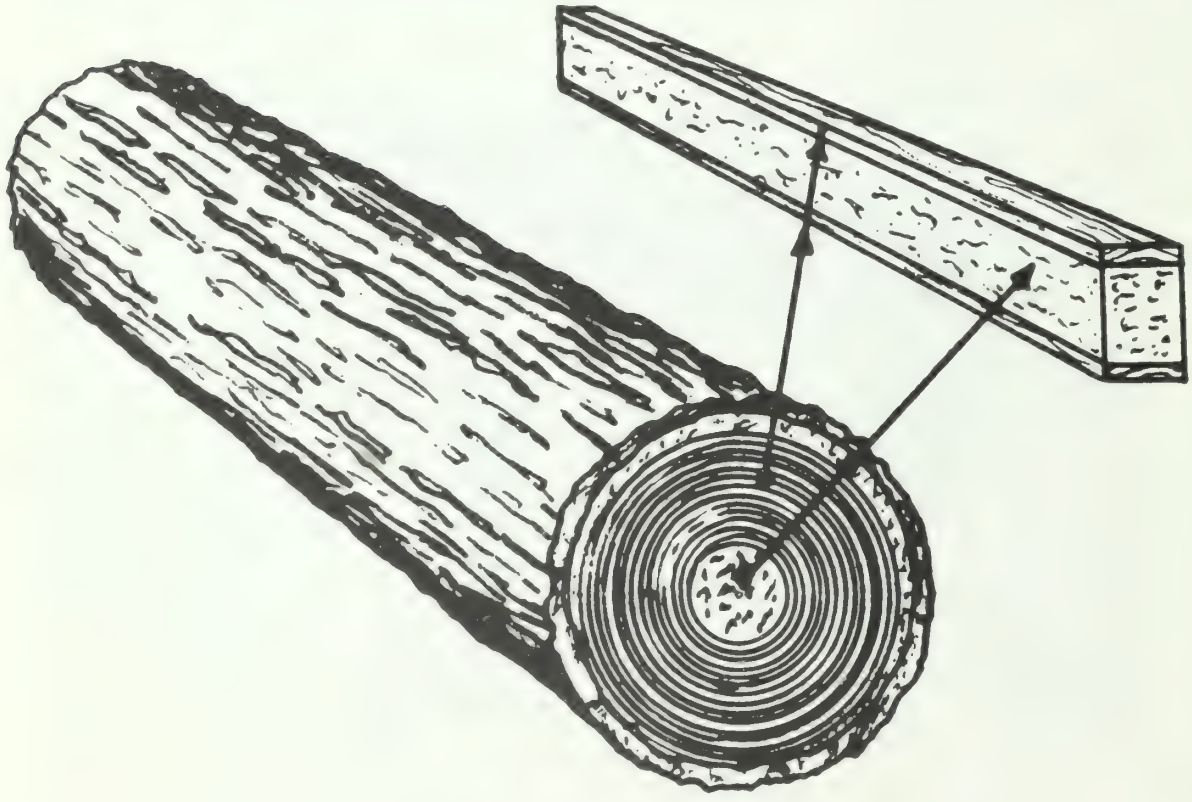

Figure 10.--The composite concept.

With the COM-PLY concept, the wood of the tree is put together in the most efficient manner for specific uses. Even trees of different species can be combined to make a piece of composite lumber. The Wood Products Research Unit has made COM-PLY studs with hardwood veneers of oak, hickory, and yellow-poplar, as well as southern pine, sometimes with layers of veneer from different species in the same stud. Many different sizes and types of nails were driven into the veneer faces of studs made with dense species such as oak. These studs were easy to nail and split less than when similar nails were driven into southern pine veneers.

Hardwoods can also be used in the particleboard cores of COM-PLY lumber. In fact, hardwood has been used in combination with softwood to make commercial particleboard for many years. As previously pointed out, however, only a small percentage of our abundant hardwood resource is presently used for lumber and sheathing in houses. Using more hardwood in housing construction would provide a larger timber supply closer to eastern population centers, thereby reducing the pressure on softwoods.

Product Performance

Knots, cross grain, and holes often weaken solid sawn lumber and cause it to warp. A large knot or several knots can diminish strength and stiffness as much as 50 percent. The design of COM-PLY studs prevents this problem. Because each stud is faced with four layers of veneer, there is little chance that cross grain or a series of large knots will occur in more than one layer of veneer at a given cross section. Indeed, tests by the Wood Products Research Unit showed that COM-PLY studs are uniformly stronger and stiffer than sawn lumber studs.

Sawn lumber also shrinks or swells with changes in moisture content. If a builder constructs a wall with warped studs, the wall will bow and be crooked. In COM-PLY studs, however, the laminated construction eliminates any tendency to warp.

The Wood Products Research Unit made COM-PLY studs with phenolic and phenol-resorcinol resin binders similar to those needed for exterior-grade or marine plywood. These studs were then exposed to steaming and soaking (fig. 11) in accelerated aging tests and to one year of outdoor weathering (fig. 12) on a test fence (Duff, in press). Subsequent tests on these studs revealed that their strength and stiffness remained well above the limits required for wall studs in residential construction (Blomquist and others 1976).

COMPOSITE PANELS

Composite panels are designed as substitutes for plywood panels. Like composite studs, they contain a particleboard core, and the outer surfaces consist of veneer sheets. These panels will vary in thickness according to whether they are to be used as roof sheathing, flooring, etc. The most common thickness for structural panels is 1/2 inch. Composite panels of this thickness would have a sheet of 1/10-inch-thick veneer on each face (fig. 13). Such panels would consist of 60 percent particleboard and 40 percent veneer. Thin composite panels (3/8 inch) would be about half veneer and half particleboard, whereas thick composite panels (3/4 inch) would be about one-third veneer and two-thirds particleboard.

Utilization

With present methods of manufacturing plywood, about 45 percent of the volume in a veneer log or peeler block ends up as plywood, and the rest is residue (fig. 14). Composite panels, on the other hand, utilize the entire volume of the peeler block because the residues generated from making the veneer are used in the particleboard core. Thick composite panels would also require additional residues for the particleboard cores, whereas thin panels could be made entirely from the material in the peeler block itself. In fact, a manufacturer making both thick and thin composite panels could use almost all of the tree stem that can be economically harvested.

Figure 11.--Composite studs in tank used for steaming and soaking in accelerated aging test.

Figure 12.--Composite studs on an outdoor test fence at Athens, Georgia.

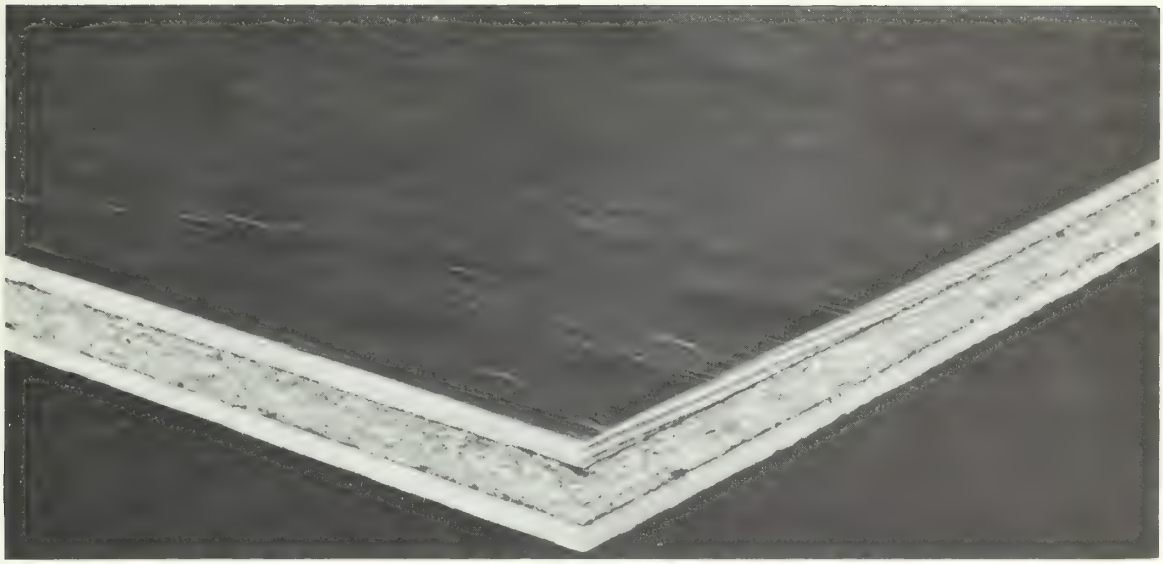

Figure 13.--A section of a 1/2-inch-thick composite panel.

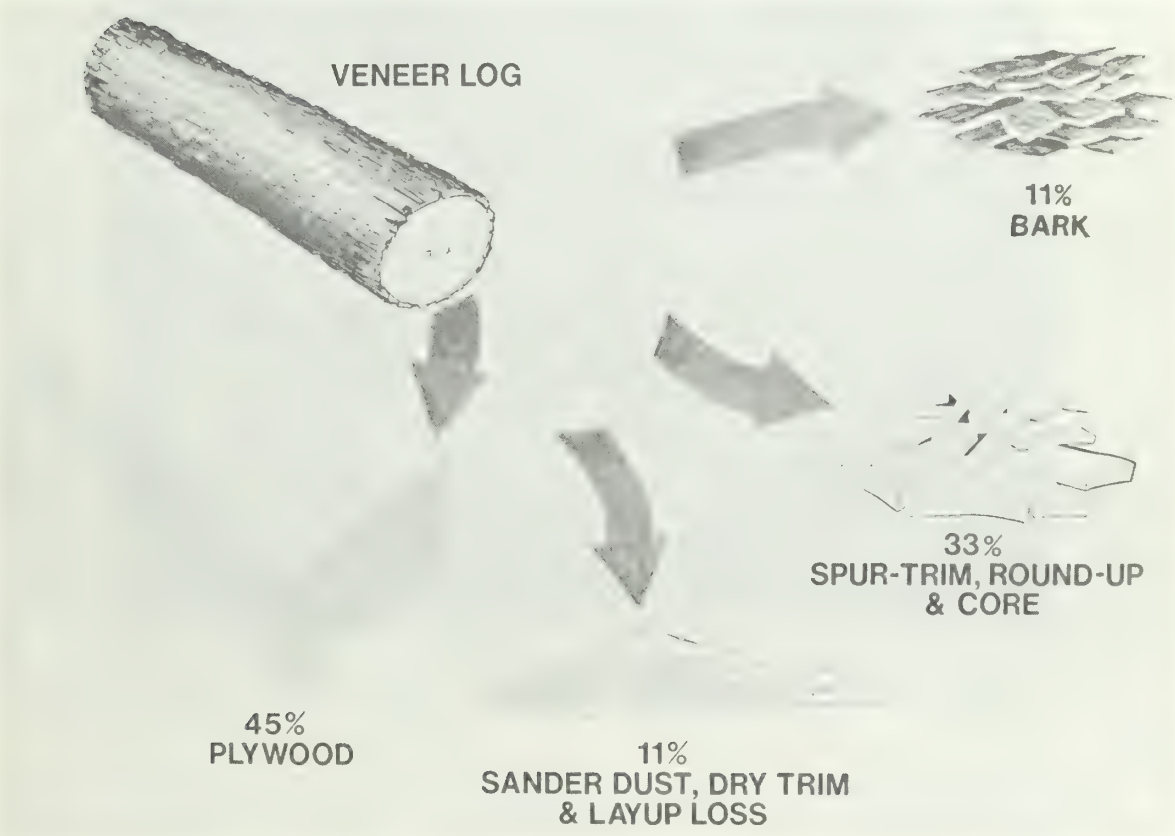

Figure 14.--Conversion of veneer logs into plywood.

Plywood mills located in areas with a limited supply of timber can reap great benefits by converting their production to composite panels. A composite mill needs less than half as many trees for raw material as does a plywood mill. Thus, converting to composite production would more than double the supply of timber available to plywood mills with limited raw materials.

Product Performance

On the average, a composite panel is stronger and stiffer along its long axis and less strong and stiff along its short axis than is a plywood panel of the same thickness. Because the principal direction of stress in a panel is along its length, composite panels are stronger than plywood for most uses.

Extensive laboratory tests by the American Plywood Association have demonstrated that composite panels have structural and durability properties equaling or exceeding those of plywood (Carney 1976a). In some 300 tests of impact load, composite panels performed at well over the load levels anticipated during construction and service (fig. 15). Laboratory and outdoor tests showed that composite panels can meet the durability and strength requirements for roof sheathing, subflooring, and single-layer floors in residential construction (fig. 16).

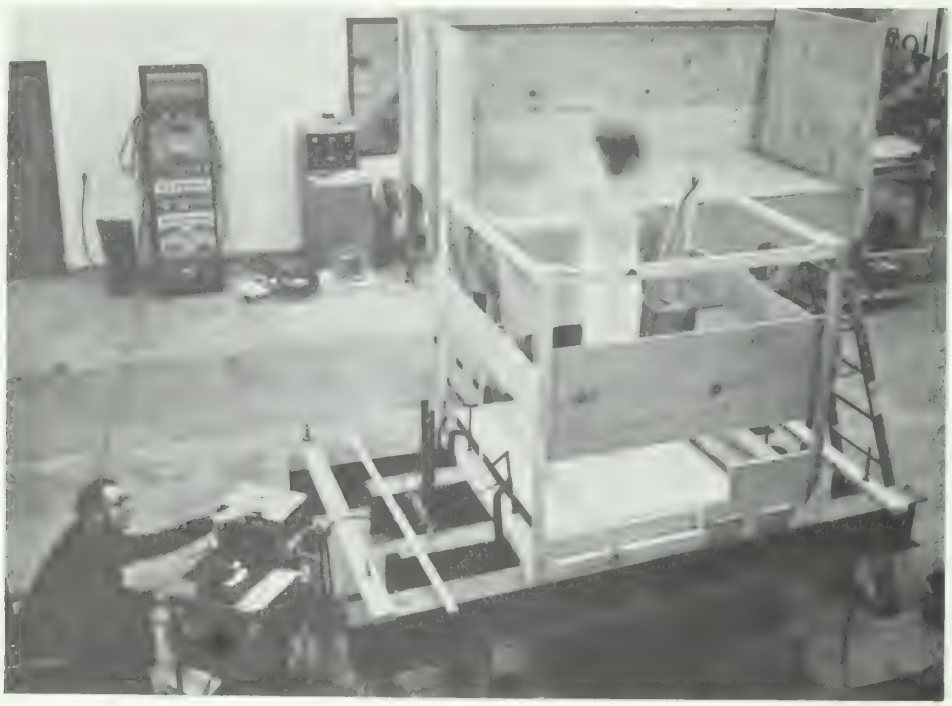

Figure 15.--In-service impact loads were established by having people jump on composite panels.

As previously noted, all wood products shrink or swell somewhat when they lose or gain in moisture content. In plywood, dimensional stability is maintained by orienting the grain of the inner plies at a 90° angle to the grain of the face plies. If composite panels are to have similar dimensional stability, most of the wood particles in the core must be oriented with their grain at a 90° angle to the two veneer sheets (fig. 17). Such orientation is possible if the residues from veneer manufacture are chipped and milled into wood particles four or five times

longer than they are wide. Special machinery can then align the elongated wood particles across the width of the particleboard core.

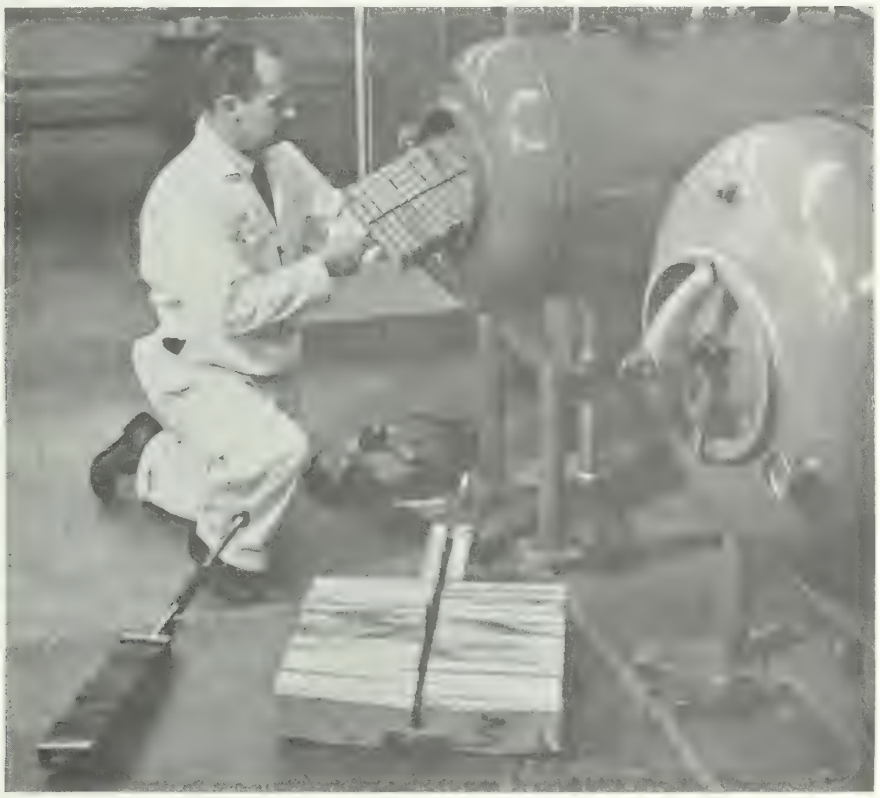

Figure 16.--Test specimens of composite panels were cycled in vacuum-pressure vessels and dried in electric ovens to simulate moisture changes during use.

EFFECT ON FOREST MANAGEMENT

Manufacture of composite products promises to improve opportunities for forest management while it provides a market for previously unused wood and residues. Unlike conventional mills, a factory manufacturing composite lumber and panels could utilize small logs from tree tops and sound wood from diseased, crooked, and fire-damaged trees. Composite products could utilize as much as one-fifth of the 9.6 billion cubic feet of residues left in the forest each year because they are unsuitable for conventional lumber and plywood (fig. 18). Such utilization would not only reduce the fire hazard in our forests and eliminate the unpleasant sight of tree tops and broken trees after logging operations, but it would also reduce the cost of site preparations before new stands of trees are planted.

Composites will also allow us to better utilize our standing timber. During the past century, loggers generally harvested the species of tree in greatest demand. Trees that produced lower-quality wood products were left in the forest and often generated the next stand of timber. To a large extent, this is still a problem. When a southern pine stand is cut for lumber or plywood, for example, loggers leave many hardwoods on the site (fig. 19). Such areas often become hardwood forests and help create greater shortages of needed softwood timber. Incorporation of hardwoods into composite products will provide a market for these species and free valuable acreage for replanting to pine.

Figure 17.--Orientation of wood particles in the core of a composite panel.

Climate and soil type on some forest lands are best suited for trees other than those used for conventional lumber and plywood. Nevertheless, foresters are often asked to plant such sites to the timber species in greatest demand. Use of a mixture of species in composite products will give foresters greater freedom to grow tree species best suited to available sites.

Incorporation of a mixture of species in composites will also allow foresters to reduce the large acreages now devoted to growing a single species. This monoculture represents a potential threat because an epidemic of disease or insects might destroy vast amounts of such holdings in just a few years. Thus, composite products will not only provide for greater utilization of present timber resources but also for better management of tomorrow's forests.

ECONOMIC FEASIBILITY OF PRODUCING COMPOSITES

Probably the greatest economic advantage of composite panels and lumber is that they utilize more wood from each tree than do conventional products. Cost of standing timber accounted for about 10 to 15 percent of lumber prices early in this century and will probably approach 50 percent when the century ends (USDA Forest Service 1973). Thus, wood products that can more completely utilize trees have a distinct cost advantage as long as the savings in wood costs are not offset by rising prices for labor, adhesives, and overhead.

A second economic advantage of composite products is the better opportunity they provide to adjust factory production to periods of recession and prosperity.

Peaks in production of plywood, particleboard, and lumber occur at slightly different times. Peaks for lumber and plywood are closely tied to home-building cycles, whereas those for particleboard usually occur a year or two thereafter. Production of particleboard lags because this product is used primarily in items and buildings--furniture, display cases, shopping centers, schools--in greatest demand after a housing boom. By shifting its production as demand shifts, a factory manufacturing both composites and particleboard could therefore operate at a peak and maintain full employment for longer periods than conventional mills.

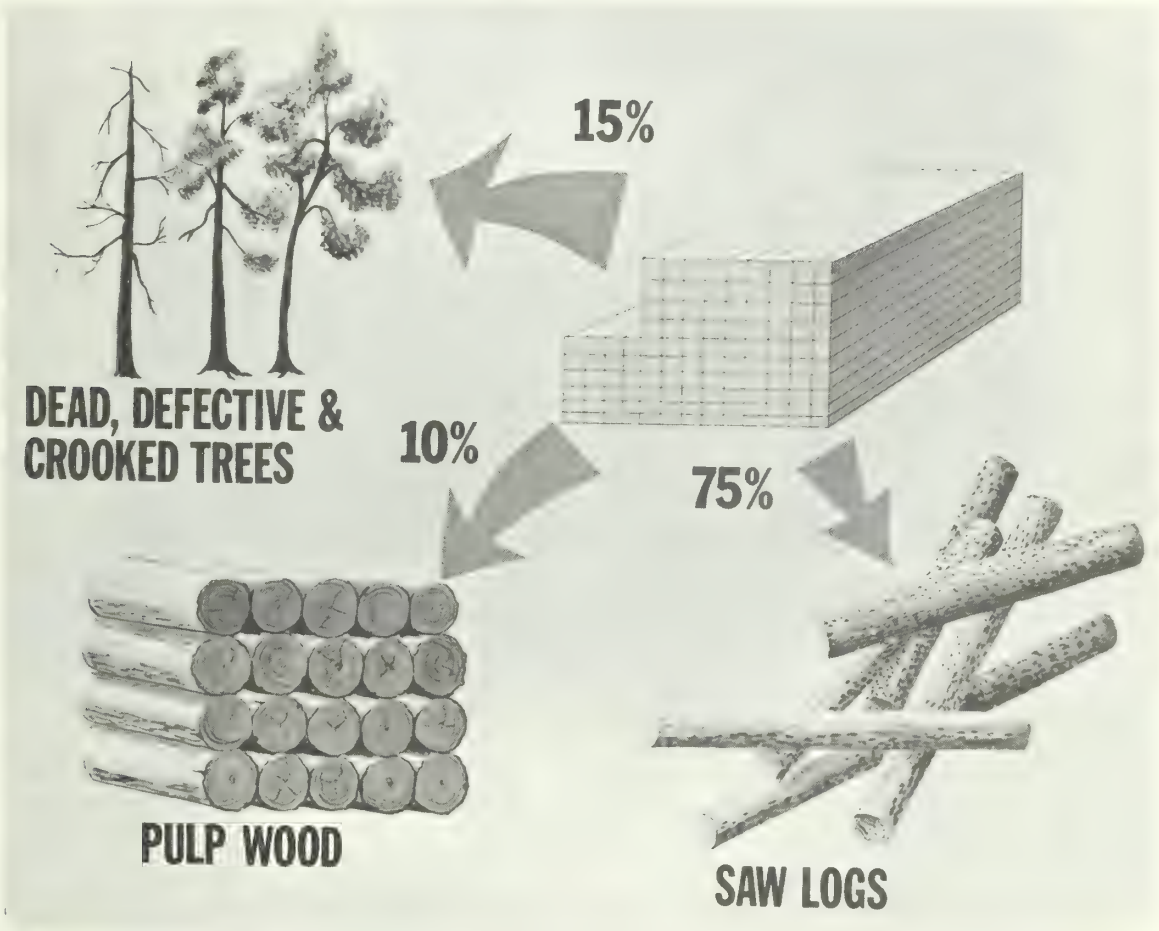

Figure 18.--When timber is harvested for conventional lumber, 75 percent of the volume ends up as saw logs, 15 percent is left in the forest, and 10 percent is used as pulpwood.

Composite products also have a distinct economic advantage because they can be manufactured from various timber species. As softwood prices rise during periods of peak production, composite factories in the East could supplement their raw material with hardwood, which maintains more stable prices during fluctuations in the business cycle.

Figure 19.--Hardwood trees left after harvesting southern pine from a site.

COMPOSITE LUMBER

In 1975, a cost analysis by Koenigshof (1975) showed that a factory in Arkansas could have manufactured an 8-foot COM-PLY stud composed of both hardwood and softwood for 60 cents:

	Cents per stud
Wood	15.1
Particleboard resin	16.6
Laminating glue	6.0
Labor	5.7
Overhead	16.1
Total	59.5

The average selling price for a solid, sawn stud in 1975 was 66 cents at the mill. The cost analysis also showed that there would be a 22 percent return on the factory investment for COM-PLY manufacture and that the investment would be paid back in 8 years if the cost of borrowing capital was 15 percent. Thus, if COM-PLY studs were sold at the same price as sawn studs, their manufacture in Arkansas during 1975 would have been profitable and would have offered an acceptable return on the investment:

	Cents per stud
Selling price	66.0
Manufacturing cost	59.5
Before-tax profit	6.5
Income tax	3.1
After-tax profit	3.4

In 1976, the opportunities for profit from manufacturing COM-PLY studs were even greater.

COMPOSITE PANELS

In 1975, unpublished studies by Koenigshof showed that a factory in Arkansas could have manufactured a 1/2-inch-thick composite panel (CD exterior grade) measuring 4 by 8 feet for $4.01 and a plywood panel of the same dimensions for $4.22:

	Composite panel	Plywood panel
	(Dollars)	(Dollars)
Wood	1.28	1.74
Resin and wax	.70	.62
Labor	.84	.62
Overhead	1.19	1.24
Total	4.01	4.22

Thus, composite panels would have been more profitable to produce in 1975 than equivalent plywood panels.

Further documentation of the economic feasibility of manufacturing composite products, both panels and studs, will be published in a forthcoming report by Koenigshof.

ACCOMPLISHMENTS OF THE COM-PLY RESEARCH PROJECT

COMPOSITE LUMBER RESEARCH

The Wood Products Research Unit at Athens, Georgia, has prepared a series of COM-PLY reports on various facets of its research. These reports will soon be available from the Southeastern Forest Experiment Station and the U.S. Department of Housing and Urban Development (HUD). The following sections highlight some of the important findings from these reports.

Veneer Yields

As part of the COM-PLY research program, McAlister (in press) measured the veneer yield from carefully selected loblolly and slash pines representative of southern pine timber. It was in this study that it was discovered that the entire stem of the tree can be converted into composite lumber. McAlister's tallies of veneer yield by volume and grade will be useful to prospective manufacturers in estimating wood requirements and costs for producing COM-PLY studs.

Performance Standards

Performance standards for COM-PLY studs in residential construction have been developed by Blomquist and others (1976). Addressed to manufacturers, building code officials, and home builders, these standards set forth the required levels of strength, stiffness, durability, dimensional stability, and nailed joint strength

for COM-PLY studs and give directions for testing and measuring actual performance. Prospective manufacturers are free to use any wood species, thickness of veneers, resin binders, and laminating adhesives deemed economically feasible as long as representative samples of the proposed studs meet the performance standards. Thus, adoption of these standards will enable home builders and building code officials to be certain that any marketed COM-PLY studs are safe for use in home building.

Laboratory and Field Tests

Several reports describe laboratory and field tests on COM-PLY studs. Wittenberg (in press) tested the strength and stiffness of studs made with various numbers and thicknesses of veneers (fig. 20). His tests show that studs made with two southern pine veneers about 1/7 inch thick will simultaneously support a 1,190-pound end load from floors and roofs and 20 pounds per square foot of lateral load from wind pressure. This report will help guide manufacturers designing their own COM-PLY studs.

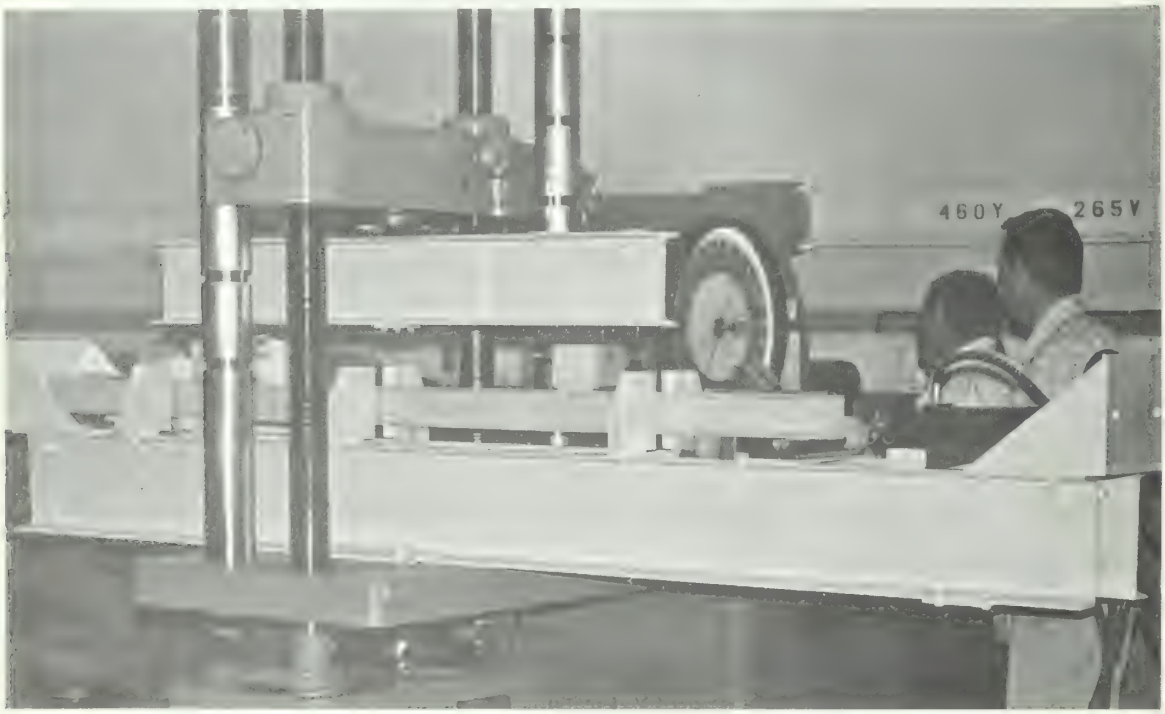

Figure 20.--COM-PLY stud being tested for strength in a universal testing machine.

Walker (in press) tested the strength of various nailed joints composed of COM-PLY and spruce studs (fig. 21). He found that COM-PLY studs equal or exceed spruce studs in nail withdrawal and lateral load resistance. End-nailing, toe-nailing, and face-nailing with several sizes and types of nails indicated that the nailed joint strength of COM-PLY studs is sufficient for home building.

Duff (in press) subjected COM-PLY studs to outdoor exposure tests and accelerated aging in the laboratory. After repeated cycles of steaming, drying, and water soaking that simulated several years of outdoor weathering, the studs showed excellent durability, losing only 16 percent of their strength and retaining almost all of their stiffness. Losses in strength and stiffness after one year of outdoor exposure were also relatively small. Duff's most exciting finding was that the

studs remained essentially warp-free after being soaked in water and dried. He concluded that COM-PLY studs are sufficiently durable and dimensionally stable for use in house construction.

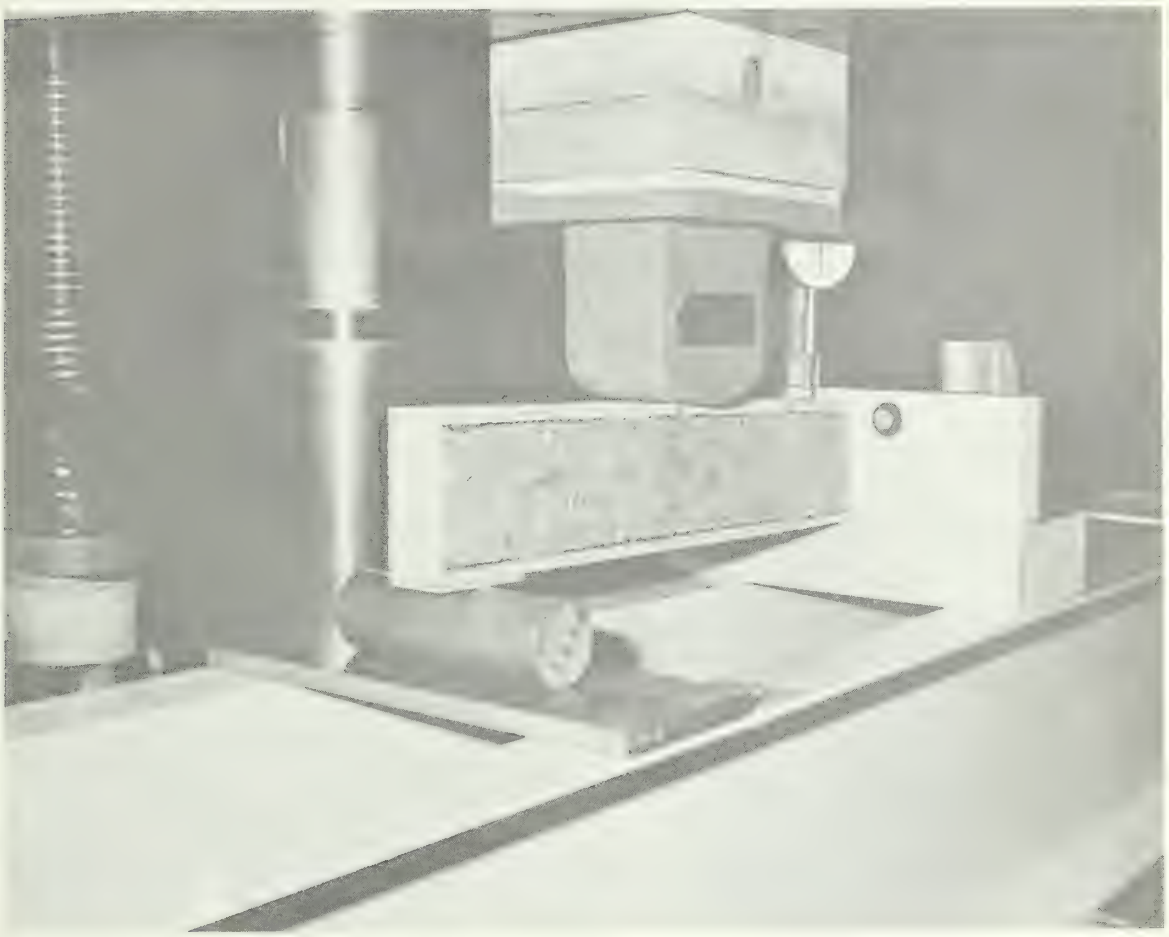

Figure 21.--Nailed joint being tested for strength in a universal testing machine.

Manufacturing COM-PLY Studs

After designing COM-PLY studs in the laboratory, the Wood Products Research Unit cooperated with private industry in manufacturing them on production-line equipment. Georgia-Pacific's particleboard plant at Vienna, Georgia, produced 260 particleboard panels, each 1-1/2 inches thick by 4 feet wide by 8 feet long, with phenolic binder. Champion-International's U.S. Plywood division supplied 1/6-inch-thick southern pine veneer from their plywood plant in Waycross, Georgia. They then laminated the veneer into two-ply sheets (4 by 8 feet) with phenolic resin adhesive on a standard plywood hot-press. The sheets of veneer and particleboard panels were then shipped to the U.S. Plywood factory at South Boston, Virginia, where a circular-gang saw ripped them into widths suitable for fabricating studs.

At South Boston, 3,200 COM-PLY studs were fabricated in a lumber edge-bonding machine (fig. 22). Roller-type spreaders covered both narrow edges of the particle-

board cores with phenol-resorcinol adhesive (fig. 23). Next, a pair of two-ply veneer strips was placed behind each stud core, and the strips and cores were continuously fed into the lumber edge-bonding machine. Constant pressure was kept on the gluelines of the studs as they passed between steam-heated platens (350° F) that cured the adhesive. This fabrication on production-line equipment demonstrated the practicality of using conventional methods to manufacture COM-PLY studs. Details of the factory laminating process are given in a report by Vick (in press).

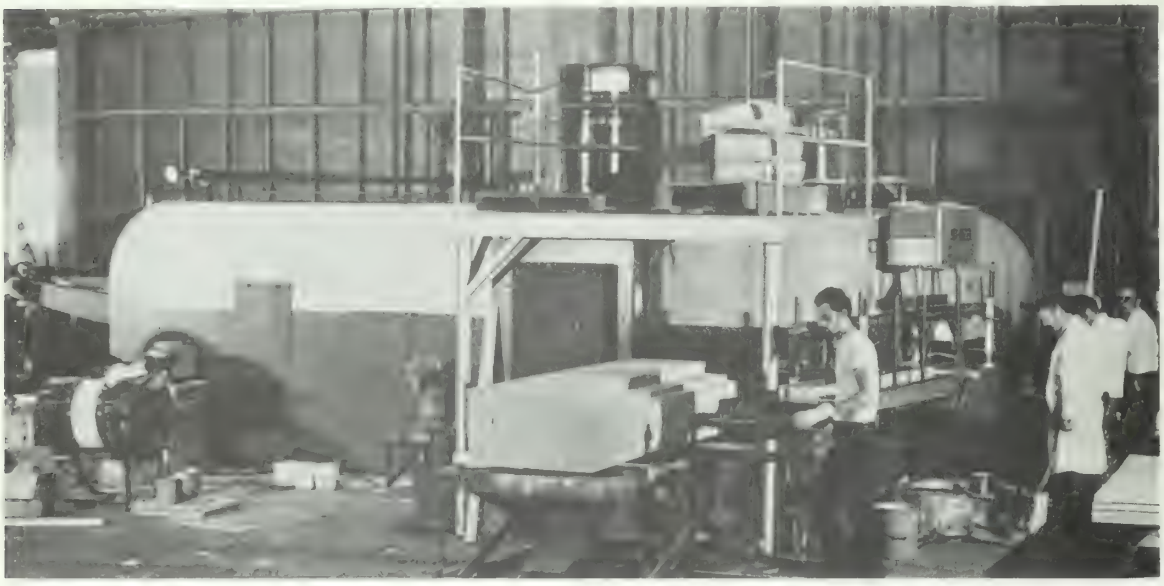

Figure 22.--Veneers were laminated to particleboard cores in this lumber edge-bonding machine.

Demonstration Houses

Four demonstration houses were constructed with COM-PLY studs to test the performance of the new product under actual service conditions. These houses were built in the Northwest, Midwest, East, and Southeast. Builders used the COM-PLY studs as they would sawn studs and were asked to compare the two products.

At each building site, the COM-PLY studs were left unprotected until they were installed. Rain drenched some of the houses during construction. At the midwestern house, which was built near Chicago in February, the exposed studs were sometimes covered with ice and snow (fig. 24). All of the studs withstood this weathering without apparent damage.

For the eastern house, the exterior wall panels and interior wall partitions were prefabricated with COM-PLY studs at a factory (fig. 25). All of the other houses were constructed onsite. In both shop and field construction, the builders found that COM-PLY studs could be cut, nailed, and installed essentially like solid, sawn studs (fig. 26).

All of the builders commented that the COM-PLY studs were heavier than the western white fir and spruce studs they were accustomed to. This extra weight was the result of fabricating the COM-PLY studs from southern pine, a heavier wood than white fir and spruce. Furthermore, the core of the COM-PLY studs had a slightly higher density than was called for in the specifications (Maloney 1973). COM-PLY

studs made of southern pines will weigh about the same as solid studs made from these species.

Figure 23.--Adhesive spreaders covered both narrow edges of the particleboard cores with laminating adhesive.

Figure 24.--At the midwestern site, COM-PLY studs were sometimes covered with ice and snow.

The builders were unanimously enthusiastic about the straightness of COM-PLY studs (fig. 27). In fact, they expressed a preference for COM-PLY over solid studs as long as the two products cost the same. They felt that the lack of warp in the new product resulted in straighter walls and fewer wasted studs. They also pointed out that straighter studs would make it easier to surface and hang cabinets and to assemble and join prefabricated panels.

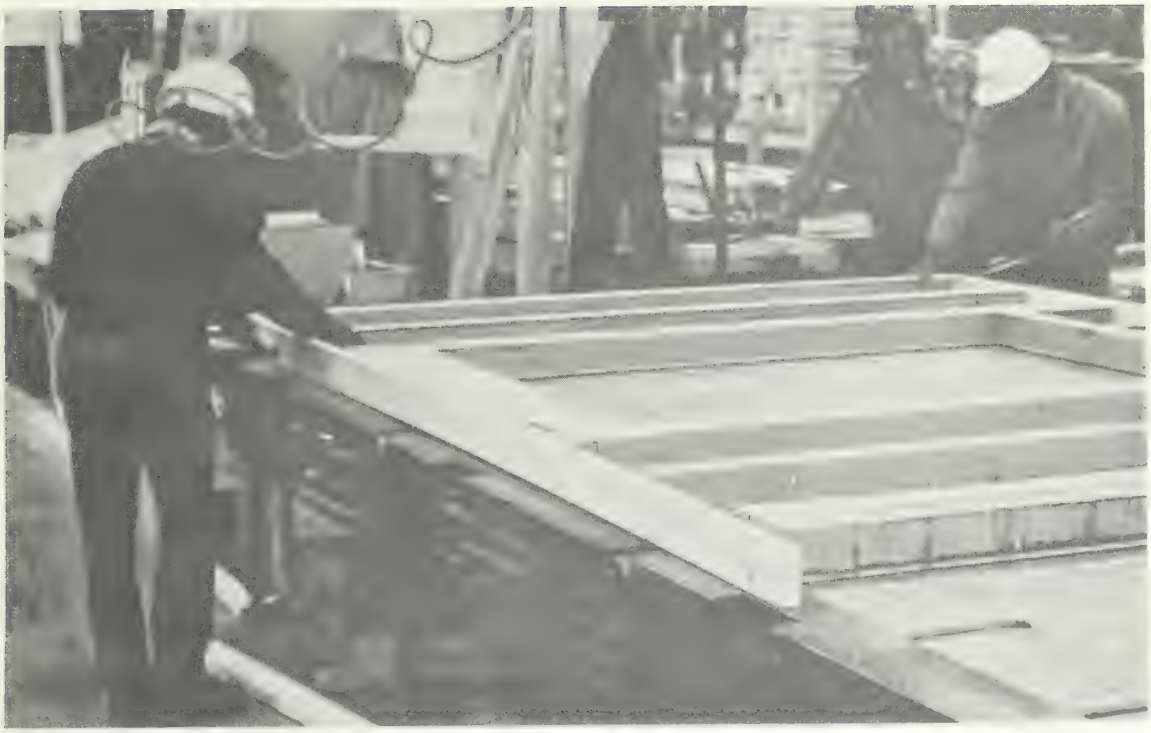

Figure 25.--Prefabricating wall panels with COM-PLY studs at a factory.

Figure 26.--Nailing COM-PLY studs into a wall frame at the building site.

Figure 27.--Builders were impressed with the straightness of COM-PLY studs.

Local building officials who inspected the houses indicated that COM-PLY studs would be acceptable if they met laboratory tests. Construction of the demonstration houses is described in greater detail in a report by Koenigshof and others (in press).

COMPOSITE PANEL RESEARCH

Laboratory and Field Tests

Laboratory research by the American Plywood Association on composite panels for floors and roofs has been reported in detail by Carney (1976a). The APA researchers developed an accelerated test to measure durability of the bond between the veneers and the particleboard core. The test is suitable for quality control and has been correlated with one-year outdoor exposure tests. The accelerated test evaluates both the core and the gluebond and can be used to evaluate composites made with various cores and resins.

APA also determined the structural performance required of composite panels. In devising these requirements, the researchers applied point loads, both static and impact, rather than the conventional uniform load because point loads more closely represent actual conditions in service (fig. 28). Sizes of expected service

loads were determined from a survey, and the required stiffness was determined from the acceptable performance of plywood. From these requirements, the researchers developed test methods and criteria which permit meaningful evaluation of any composite panels that may be produced for use as floor or roof sheathing.

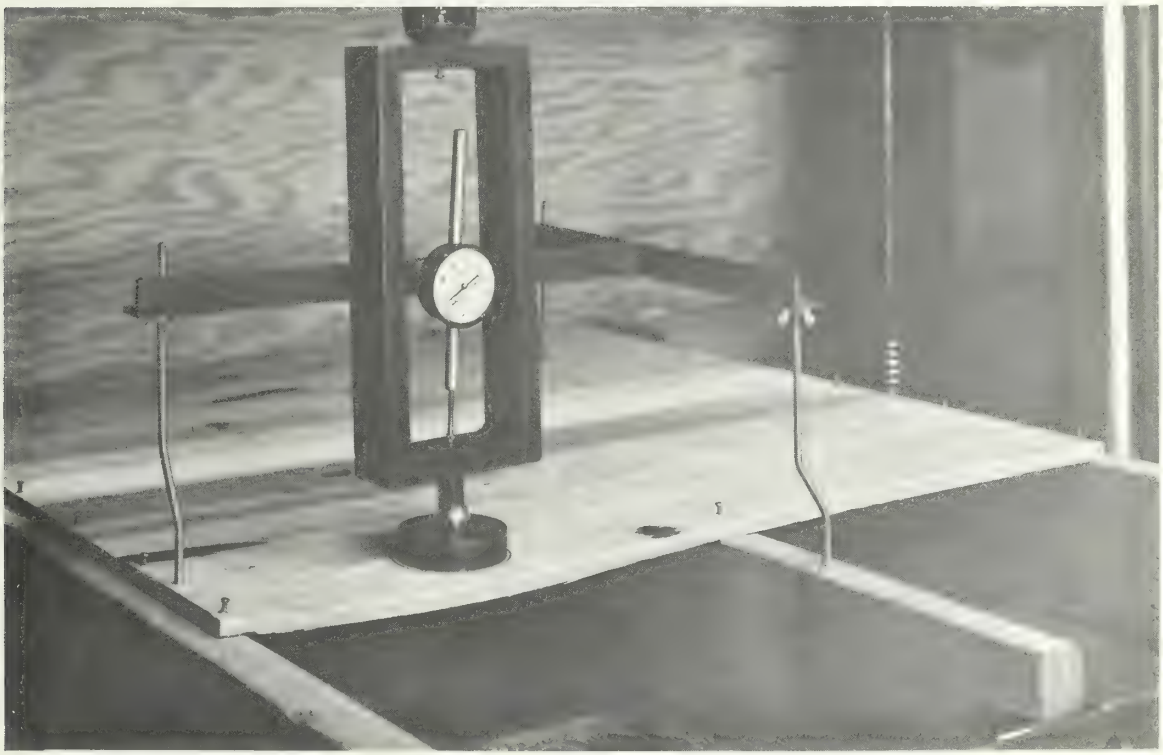

Figure 28.--A point load was applied to the edge of a composite panel to simulate load on adjoining edges of floor panels.

The bending strength of composite panels was also evaluated (fig. 29). APA researchers developed methods of calculating stiffness parallel to the face grain on the basis of properties of the individual layers in the composite. They also developed a method of calculating strength parallel to the face grain by comparing composite panels with three- or four-ply plywood. Composites proved to be significantly stiffer than plywood, although slightly weaker, under point loading.

To assist potential manufacturers, APA prepared tables that show how the properties of composite panels compare with those of plywood (Carney 1976a). It has also decided to apply its quality grademark, similar to that used in grading plywood, to commercially produced composite panels. The performance requirements it developed for composite panels used in roofs and floors have been reviewed by officials of various model building codes, and its test method has been submitted to the American Society for Testing and Materials for consideration as a standard.

A brief report summarizing APA's laboratory research on composite panels has been prepared by Carney (1976b) and is available from the Wood Products Research Unit in Athens, Georgia, and from the Division of Research and Technology at the Department of Housing and Urban Development in Washington, D.C.

Figure 29.--Bending strength of composite panels was tested with a post flexure machine.

Demonstration Houses

APA also built two demonstration houses with composite panels. One was constructed near Washington, D.C., and the other near Portland, Oregon. In the western house, composite panels were used for single-layer floor (fig. 30) and roof sheathing (fig. 31) and for single-layer wall siding (fig. 32). In the eastern house, the panels were used only for single-layer floor and roof sheathing. Builders handled, cut, nailed, and installed the composite panels essentially as they would plywood. Rain soaked the western house many times during construction, and water stood on the composite floor for several days without damaging it. Details on the construction of these houses are reported by Koenigshof and others (in press).

Producing Composite Panels

The composite panels for the demonstration houses were produced by private industry. Potlatch Corporation supplied both roof and floor panels, Weyerhaeuser Company supplied roof panels for one house, and Evans Products Company supplied wall siding panels for one house.

The most significant result of the cooperative research on composite panels is that private industry has decided to manufacture them commercially. In January 1976, Potlatch Corporation opened the Country's first factory for producing composite panels in Idaho (fig. 33). Factories of other major manufacturers of forest products are expected to begin producing composite panels in early 1977 (Koenigshof 1976).

Figure 30.--Composite panels were installed just like conventional plywood for single-layer floor sheathing.

FUTURE DIRECTION OF THE PROGRAM

Although some composites are already being manufactured, it will be perhaps a decade before they are in widespread use. Even after all laboratory research has been performed, composites must undergo 1 to 2 years of pilot plant production so that industries can be certain of manufacturing techniques, the economics of production, and acceptance by building codes and consumers. Time will also be required for private industries to build new or convert old factories and to provide the necessary sales and distribution system for the new products.

Thus far, the COM-PLY research project has been limited to developing exterior wall studs and panels for floor and roof sheathing. The next phase of research will be to develop COM-PLY floor joists for house construction. These joists will be subjected to fire and acoustical tests, as will COM-PLY wall studs, and the economic feasibility of their manufacture will be determined. The concept of composite panels will be extended to include sidings, concrete forms, and other specialty products.

Figure 31.--Composite panels were applied like plywood for roof sheathing.

Figure 32.--Composite panels were used as single-layer wall siding.

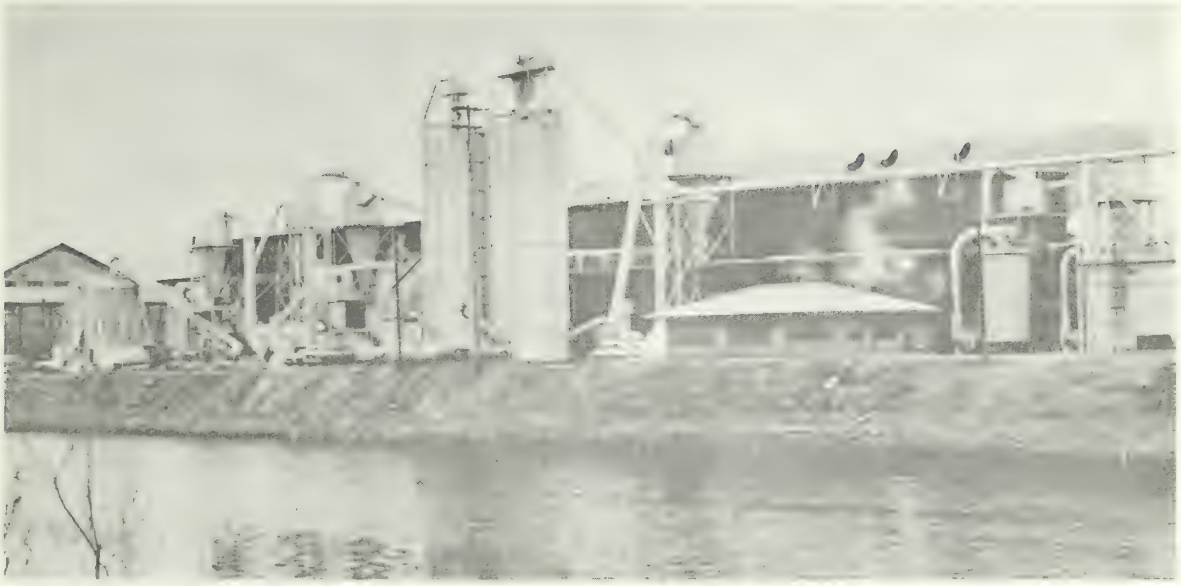

Figure 33.--Potlatch Corporation's factory for producing composite panels, the first in the United States.

In addition to its work on new COM-PLY products, the Wood Products Research Unit will study yields and strength properties of hardwood veneer that can be used in composites. It will also evaluate economical laminating adhesives and durable resin binders for particleboard. Efforts will be made to devise a particleboard with the greatest possible strength, stability, stiffness, and durability for composite constructions.

The future of composite products is encouraging. Continued cooperative research by the Forest Service, the Department of Housing and Urban Development, the American Plywood Association, universities, and private industry will help to assure Americans of an ample supply of wood products at reasonable costs.

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This report describes the development of composite wood or COM-PLY products to be used as lumber and panels in light frame construction. Composites combine veneer and particleboard in a manner that can more than double the yield of structural wood products from a single tree. The report describes demonstration houses built with composite lumber and panels made on production-line equipment. It also discusses how the new composite products will extend our forest resources and improve forest management.

KEYWORDS: Composite lumber, composite panels, particleboard, veneer, wood utilization, house framing, house sheathing, wood products.

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USDA Forest Service Research Paper SE-167 May 1977

COM-PLY 4 REPORT

LAMINATING COM-PLY STUDS IN A FACTORY

COOPERATIVE RESEARCH

LAMINATING COM-PLY STUDS IN A FACTORY

by

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Forestry Sciences Laboratory

Athens, Georgia

Cooperative Research by

U.S. Department of Agriculture, Forest Service

Southeastern Forest Experiment Station

and

U.S. Department of Housing and Urban Development

Division of Energy, Building Technology

and Standards

PREFACE

This report is one of a series on the possibilities of producing house framing and structural panels with particleboard cores and veneer facings. These COM-PLY or composite materials were designed to be used interchangeably with conventional lumber and plywood in homes. Research on structural framing is presently limited to COM-PLY studs but will be extended to include larger members such as floor joists.

In 1973, the home-building industry faced a shortage of lumber and plywood and consequent rising prices. Both industry and government recognized that this situation was not a temporary problem, and that long-range plans for better using the Nation's available forest resources would be necessary to solve the problem.

The USDA Forest Service and the U.S. Department of Housing and Urban Development accelerated cooperative research on ways to utilize the whole tree. They concentrated on composite wood products made with particleboard and veneer as a way of using not only more of the tree stem, but also using less desirable trees and a greater variety of tree species than would conventional wood products. The particleboard which comprises a large portion of the COM-PLY stud is made from ground-up wood that comes from forest residues, mill residues, or low-quality timber. Thus, such composites could greatly increase the amount of lumber and plywood available for residential construction, our major use of wood, without eroding the Nation's timber supply.

Research on composite wall framing was performed by the Wood Products Research Unit, Southeastern Forest Experiment Station, Athens, Georgia. The American Plywood Association cooperated in these studies by designing and testing composite panel products that are interchangeable with plywood. Both types of products have been incorporated in demonstration houses.

Included in this series will be reports on structural properties, durability, dimensional stability, strength, and stiffness of composite studs. Other reports will compare the strength of composite and solid wood studs, suggest performance standards for composite studs, and provide construction details on houses incorporating such studs. Still others will explore the economic feasibility of manufacturing composite studs and panels and estimate the amount and quality of veneer available from southern pines. These reports, called the COM-PLY series, will be available from the Southeastern Forest Experiment Station and the U.S. Department of Housing and Urban Development.

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National Particleboard Association

LAMINATING COM-PLY STUDS IN A FACTORY

Abstract.--A simple and technically feasible method of laminating COM-PLY studs for use as wall framing in houses was successfully demonstrated in a pilot manufacturing operation. Researchers and workmen laminated particleboard and veneer with a commercial phenol-resorcinol-formaldehyde resin adhesive by using steam heat in a continuously fed, edge-bonding machine. The bondlines in these studs met the minimum performance requirements for strength and exterior durability in COM-PLY studs.

KEYWORDS: Composite lumber, sandwich construction, phenolic particleboard, veneer, pilot manufacturing operation, bondlines shear strength.

Research workers of the USDA Forest Service, in cooperation with the Department of Housing and Urban Development and leading manufacturers of particleboard and plywood, have developed a new composite building product called the COM-PLY stud. The COM-PLY stud is made of a particleboard core sandwiched between two layers of laminated veneer (fig. 1). The laminates consist of two plies, with grain direction parallel to the length of the stud. Engineered as a structural member, the COM-PLY stud is intended to be an economical and practical substitute for the conventional 2 x 4 stud in wall framing.

One of the important goals of the COM-PLY research and development program was to demonstrate the feasibility of manufacturing high-quality COM-PLY studs with commercially available adhesives and existing production equipment. It was therefore decided to produce a large number of prototype COM-PLY studs for use in several demonstration houses. These houses were to be showcases where researchers could demonstrate the practical use of composite studs. Carpenters, builders, developers, trade associations, building code officials, lending agencies, potential manufacturers of studs, and the general public wanted to know how this laboratory product performed in actual use. To accomplish this goal, researchers and workmen used existing production equipment to manufacture several thousand COM-PLY studs.

This report on the pilot manufacturing operation describes the selection and evaluation of adhesives, manufacture of the particleboard and veneer, factory lamination of the components into studs, and evaluation of the adhesive bonds in the studs.

MATERIALS

ADHESIVES

COM-PLY studs are designed to carry long-term structural loads and withstand limited exposure to weather just like solid wood studs (fig. 2). For this reason, the adhesives used to fabricate the particleboard cores, bond the veneers together, and laminate the two components into COM-PLY studs had to be the strongest and most durable types available.

Figure 1.--Cross section of a solid stud (left) and a COM-PLY stud (right).

Phenol-formaldehyde resin adhesives, which cure at high temperatures, were used for manufacturing the particleboard and laminating southern pine veneers. These adhesives are used industry-wide for manufacturing exterior plywood and particleboard.

A phenol-resorcinol-formaldehyde resin adhesive was used to bond strips of laminated veneer to the edges of the particleboard cores. This adhesive is routinely used in the wood-laminating industry. It was selected because it is the least expensive adhesive that might provide the required bond strength and durability. Furthermore, it can be partially cured at moderately elevated temperatures within minutes or at room temperature within hours. This adhesive property was essential if studs were to be laminated with a continuous edge-bonding machine.

Before this adhesive was used for production bonding, researchers performed laboratory tests to determine whether strong, durable bondlines could be made between the rough edges of the particleboard core and the veneer laminates. These

tests closely simulated anticipated operating conditions of factory assembly. Another report (Vick, in press) details specific tests and their results.

Figure 2.--Snow-covered COM-PLY studs stacked at the building site of a demonstration house. Note studs already in place as wall framing.

The phenol-resorcinol-formaldehyde resin adhesive consisted of two components--the liquid resin and powdered hardener. When the components were mixed without cooling the resin, the pot-life of the adhesive lasted from 1 to 1-1/2 hours at room temperature. Cooling the resin prior to mixing extended the pot-life to several hours.

In the laboratory, a production-type, double-roll spreader (fig. 3) satisfactorily coated both edges of the particleboard core with adhesive in one pass

through the spreader. Rubber rolls with standard grooving were suitable for applying either light or heavy spreads to particleboard edges and veneer strips.

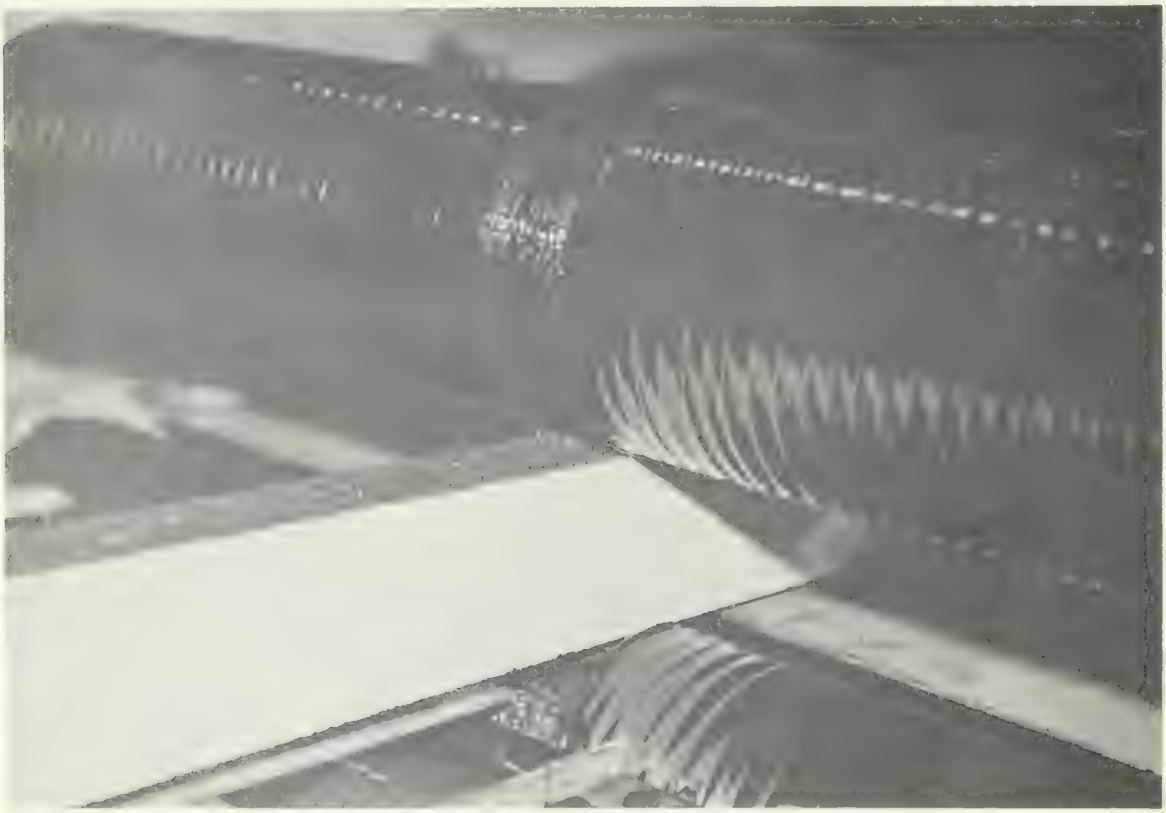


Figure 3.--Production-type, double-roll adhesive spreader coating a core.

The need for heavy spreads of adhesive became apparent early in the testing program. As can be seen in figure 4, the sawn edge of particleboard constitutes a very rough surface for intimate bonding with veneer. The veneer surface, although somewhat smoother, is also irregular. Normally, intimate contact between bonding surfaces is necessary to form strong bonds. Therefore, to achieve strong bonds between particleboard and veneer, the adhesive had to cover all particles completely; and if it was spread only on the particleboard, it had to transfer to and wet the opposite veneer surface. This condition necessitated a heavy spread of adhesive.

The laboratory tests indicated that the minimum rate for adhesive spread on a single surface (the particleboard) was 80 lb/Mft^2 (pounds per thousand square feet). At this rate, the maximum allowable closed assembly time (elapsed time after the components are assembled and before pressure is applied) was 10 minutes. Any increase in closed assembly time beyond 10 minutes at the above rate of spread caused unsatisfactory bonds. By double-spreading. i.e. spreading adhesive on both the particleboard and the veneer at a rate of 80 lb/Mft^2, the bond quality improved. Similarly, increasing the rate of single-spread from 80 to 100 lb/Mft^2 also improved bond quality. To simplify assembly of the studs and reduce manpower and equipment needed for adhesive spreading, the researchers decided to spread adhesive only on the particleboard surface. To ensure the adequacy of the adhesive bonds, they recommended a spread rate of 90 to 100 lb/Mft^2 and a maximum closed assembly time of 10 minutes.

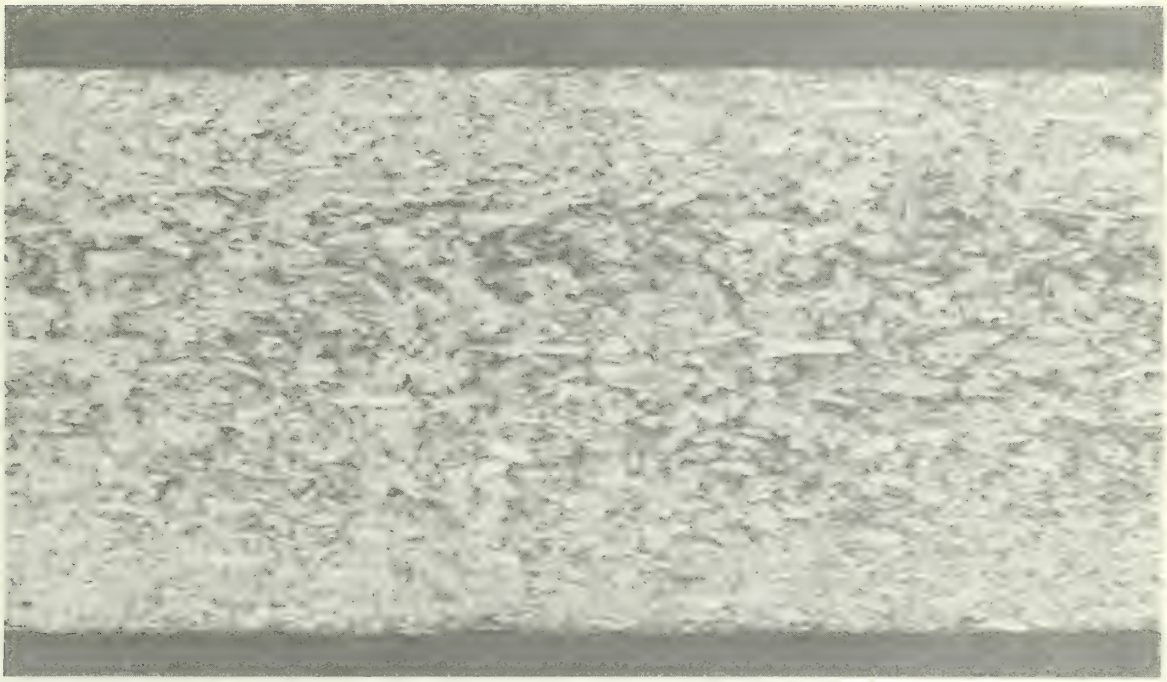


Figure 4.--Rough bonding surface of particleboard core.

These recommended assembly and curing conditions were determined from laboratory tests on southern pine veneer of normal density. However, the southern pine veneer provided for pilot manufacture of the COM-PLY studs had a very high density. Just before manufacturing the studs, researchers therefore tested their recommendations on the high-density pine veneer. The bonds between this veneer and the particleboard core were very strong, ranging from 300 to 500 lb/in^2 above the bond strength of 650 lb/in^2 for southern pine veneer of normal density. Furthermore, the bonds did not delaminate during cyclic soaking and drying. However, percentage of wood failure in sheared joints averaged as much as 12 percent below the 80 percent required in laboratory tests of bondlines. It is difficult, often impossible, to develop bonds that will produce a high level of wood failure in thick, high-density summerwood bands of southern pine.

Even though the amount of wood failure in the high-density veneer was below the acceptable level prescribed for softwood species of lower density, the bonds were still exceptionally strong and highly resistant to delamination. Therefore, researchers made no changes in the recommended assembly conditions for the pilot operation.

PARTICLEBOARD

The cores for COM-PLY studs were made from a special three-layered, flat-pressed, phenolic particleboard 1-1/2 inches thick. Researchers based their selection of this board on several considerations. First, the least dimensional change in flat-pressed particleboard occurs in the plane parallel to the surfaces contacted by the hot-press. Thus, by making these surfaces the wide faces of the stud and attaching sheathing to the veneer on the narrow faces, bowing of the walls and nail popping could be minimized (see figs. 1 and 2). A second

consideration was the findings of T. M. Maloney at Washington State University.[1/] His studies indicated that three-layered, phenolic particleboard has much better dimensional stability in the thickness direction than does board of homogeneous construction. Less change in thickness undoubtedly would improve the studs' resistance to delamination during exposure to weather. A third consideration was that the binder for particles must be strong and moisture-resistant. Phenolic binder meets this primary requirement. Finally, the adhesive, the facilities, and the know-how to make this kind of particleboard were available at the time.

Georgia-Pacific Corporation in Vienna, Georgia, manufactured the particleboard for COM-PLY studs in a special production run. This was perhaps the first 1-1/2-inch-thick phenolic particleboard ever made on a commercial production line in the United States. The particleboard was manufactured by the caul-less, flat-platen process. This particular process is normally used for making urea-bonded particleboard in thicknesses up to 3/4 inch. Thus, to use this process for 1-1/2-inch-thick phenolic board, and to achieve specific values of board density and internal bond strength, workers had to adjust the amount of binder, lengths of press time, and methods of controlling thickness.

The wood for the particleboard was southern pine that came mostly from mill residues such as slabs, edgings, and planer shavings. The particles, made by hammer-milling, were screened into two sizes. The larger particles, used in the middle layer, were splinters. Particles as fine as sawdust were used in the two outer layers of the three-layered board.

After blending the binder with the particles at various rates, the manufacturer decided on a resin content of about 8 percent on a dry-weight basis. Internal bond strength of boards with lower resin contents near 6 percent was unsatisfactory. The manufacturer blended 1 percent wax emulsion with the particles to improve the boards' water resistance.

The process of particleboard layup began with spreading controlled amounts of mixed particles and binder in three successive layers onto an endless belt. This layered mat, approximately 4 feet wide and 24 feet long, was carried by the belt to a pre-press. The pre-press compacted the mat and gave it enough cohesiveness to withstand transfer to the hot-presses (fig. 5). The mats were weighed after pre-pressing as a partial method of controlling density of the boards. Mats of acceptable weights were transferred to loading racks, then into a 14-opening hot-press (fig. 6). Special stops inserted between the presses maintained the thickness at about 1-1/2 inches. The mats were hot-pressed at 350° F for 18 minutes. As a point of reference, press time for 3/4-inch-thick urea-bonded board is typically 5 to 6 minutes. After hot-pressing, the untrimmed particleboards, still measuring about 4 by 24 feet, were hot-stacked to cure the resin completely. Then the large panels were cross-cut and trimmed to 4- by 8-foot panels.

The best 250 of these 4- by 8-foot panels were selected for the studs. The initial selection was based on internal bond and density measurements made during production. Acceptable particleboards had an average density of 40 lb/ft^3, an internal bond strength of 75 lb/in^2, a modulus of elasticity of 300,000 lb/in^2 (in the plane of the panel), and a modulus of rupture of 3,400 lb/in^2. These boards were shipped to Champion-International's U.S. Plywood particleboard plant in South Boston, Virginia, for further processing and fabrication into COM-PLY studs.

[1/] Maloney, T. M. 1973. Particleboard for composite studs. Unpubl. Res. Rep. 73/57-101, Coll. Eng., Res. Div., Wash. State Univ., 18 p. (Contract research for USDA Forest Service, Project W.O. 1308, Contract 13J-3800-8888.)

Figure 5.--Mat of particles being carried by belt into pre-press.

Figure 6.--Hydraulic hot-press applying high temperature and pressure to particleboard.

VENEER LAMINATES

As noted previously, the southern pine veneer used for the studs had high density; its specific gravity approached 0.60 when adjusted to 12 percent moisture content. Specific gravities averaging 0.50 are common in loblolly and shortleaf pines. The dynamic modulus of elasticity, as measured by nondestructive stress-wave equipment, averaged about 2.7 x 10^6 lb/in^2 for the high-density pine. Other unidentified southern pines used in earlier laboratory tests averaged about 1.8 x 10^6 lb/in^2 in modulus of elasticity.

The veneer was 1/6 inch thick, grade B and better.[2/] Veneers were laminated with phenolic resin into two-ply panels, with grain direction parallel to the panel's length in both plies. The panels measured 2 by 8 feet (fig. 7), rather than the 4 by 8 feet normally used for plywood. The veneers were laminated at Champion-International's U.S. Plywood plant in Waycross, Georgia.

Figure 7.--Two-ply veneer laminates, 2 by 8 feet, before they were ripped into 1-1/2-inch-wide strips.

[2/] Grades of veneer mentioned in this report are defined in U.S. Products Standard PS-1-74 (APA 1974).

FACTORY LAMINATION

PREPARING PARTICLEBOARD CORES

After hot-pressing, the 4- by 8-foot panels of particleboard ranged from 1-7/16 to 1-5/8 inches in thickness. After being shipped to South Boston, they were ripped into thirds (16 inches by 8 feet) so that they could be sanded to a uniform thickness of 1.52 inches. Variation in thickness of the cores would have caused incomplete contact with the hot platens of the edge-bonding machine. Panels that were too thin to be sanded were rejected. In future production, however, such sanding should be avoided because it removes the protective glaze formed during hot-pressing and makes the studs less resistant to water uptake during use.

After sanding, the 16-inch-wide panels were sawn into cores for studs. A multiple, or gang, system of circular saws made it possible to rip five cores at one time from each 16-inch-wide panel (fig. 8). After ripping, each stud core was 2-5/6 inches wide.

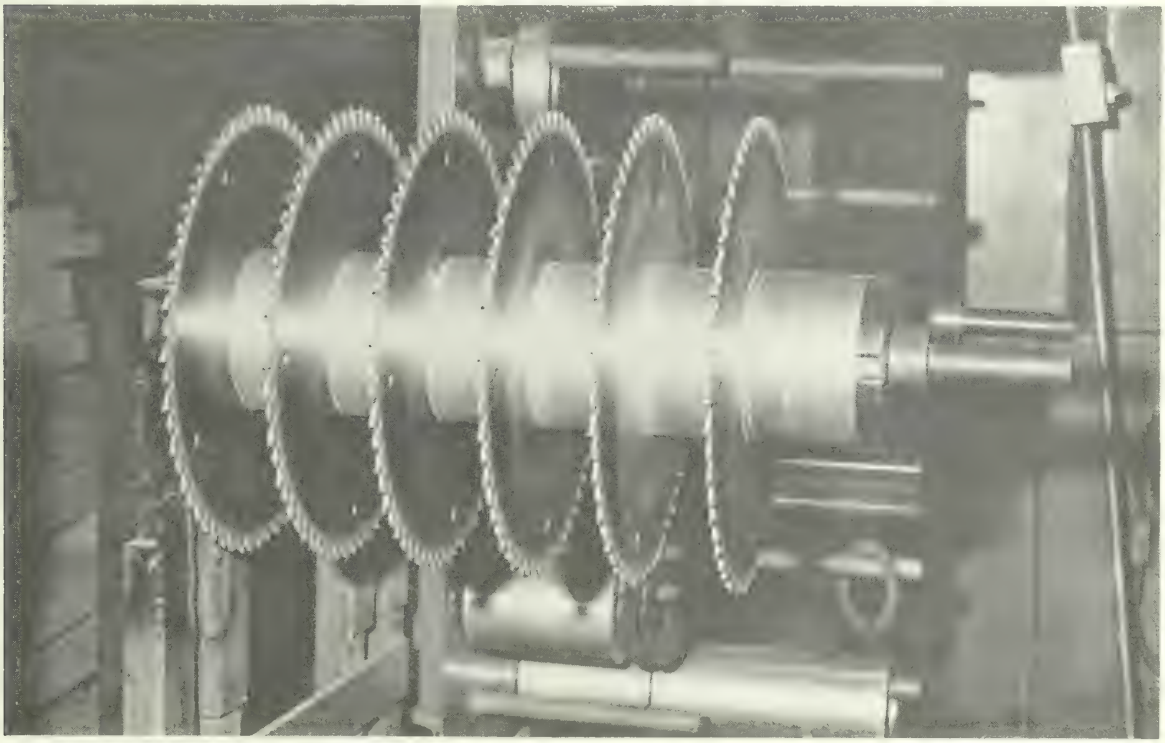


Figure 8.--Gang saws used to rip five cores.

PREPARING VENEER STRIPS

Cutting veneer laminates into 1-1/2-inch-wide strips for studs involved some experimenting with techniques. Clipping stacks of laminates with a veneer edge-clipper was too slow and failed to produce strips with even edges. More successful was gang sawing, which had been used in ripping cores from particleboard panels. This technique produced even edges with few torn slivers and allowed several panels of veneer laminates to be stacked and sawn at one time.

The veneer strips were ripped at widths of 1.510 inches. They were cut 0.010 inch less in width than the thickness of particleboard cores so that the cores could make contact with the heating platens of the edge-bonding machine.

Just before the COM-PLY studs were laminated, the veneer strips were carefully inspected (fig. 9) for any defects that would reduce their strength. Strips containing knot holes, knots, short grain, and splits in either ply were rejected.[3/]

Figure 9.--Inspecting veneer strips for defects before laminating the studs.

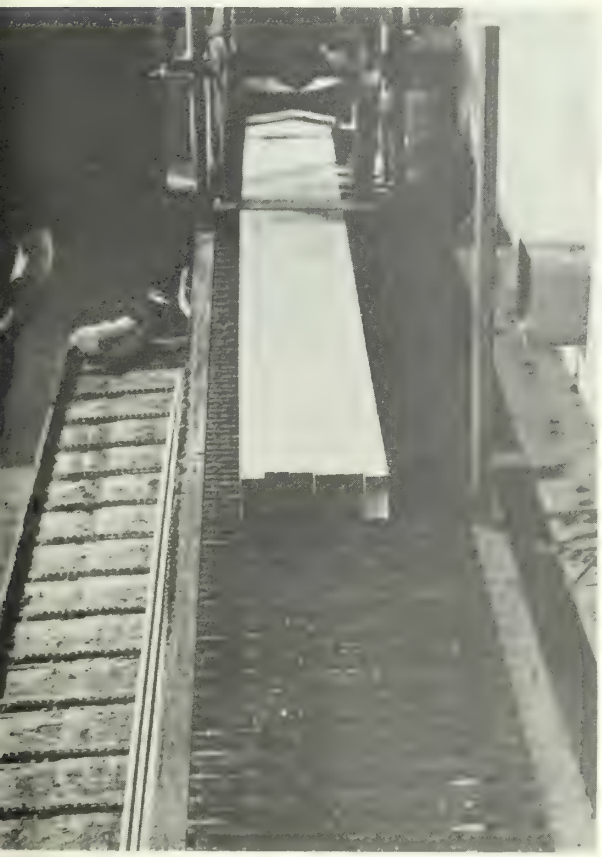
LAMINATING STUDS

Researchers and workers laminated over 3,200 COM-PLY studs with a continuously fed, edge-bonding machine at U.S. Plywood's particleboard plant at South Boston, Virginia (fig. 10). This machine is designed for high-speed edge-bonding of lumber core stock in the furniture industry. In this particular plant, it was used primarily for edge-bonding narrow widths of particleboard into full-size panels.

The laminating process began with spreading phenol-resorcinol adhesive on both edges of the particleboard cores. Rate of spread for the adhesive ranged between 90 and 100 lb/Mft^2. Application was slow because a single-roll spreader was used instead of the double rollers used in the laboratory (fig. 11). Consequently, every core had to be passed back over the spreader to coat the other edge. If a double-roll spreader had been available, it would have more than doubled the speed of operation. This speed would then have been limited only by the flow rate of the edge-bonding machine. As it was, the adhesive spreading became a bottleneck and prevented the operation from being continuous. The cores were spread with adhesive in groups of six. Uncoated veneer strips were then applied directly to each edge of the adhesive-coated cores (fig. 12), and the assemblies were immediately fed into the edge-bonding machine.

[3/] Subsequent studies by Wittenberg (in press) showed that C-grade veneer (which contains some of these defects) can be used in COM-PLY studs.

Figure 10.--Continuously fed, edge-bonding machine used to laminate COM-PLY studs. Rollers for spreading adhesive on the cores are on the right; laminated studs emerge on the left.



igure 11.--Coating six cores with adhesive on one edge by a single-roll spreader.

Figure 12.--Applying uncoated veneer strips to the edges of the adhesive-coated cores.

The direction of flow through the edge-bonding machine was perpendicular to the long dimension of the studs. Thus, the bondlines of the studs were perpendicular to the plane of the upper and lower heating platens (fig. 13). As the studs were conveyed through the machine, continuous pressure was applied to the bondlines by turning the infeed rollers faster than the outfeed rollers. Considerable pressure was also exerted on the bondlines by the friction of the studs against the upper and lower platens as the studs traveled up an incline.

Figure 13.--Orientation of bondlines in relation to upper and lower heating platens.

The steam-heated platens were 20 feet long and 100 inches wide. The original intention was to heat them to 350° F and operate the machine continuously at its slowest speed (4 feet/minute), thereby allowing each stud 5 minutes of curing time. Such a process would have cured only the outer edges of the bondlines, and the cooler centers would have been cured by residual and ambient heat after the studs left the machine and were hot-stacked. However, because of the slowness of the adhesive spreading, the machine had to be stopped and restarted after each batch of six studs was inserted. Consequently, each stud remained in the machine for 20 minutes or more and the temperature of the platens had to be reduced to about 310° F. As a result, the adhesive bonds were essentially cured when the studs were taken from the machine and hot-stacked (fig. 14).

TRIMMING, INSPECTING, PACKAGING

When the studs emerged from the edge-bonding machine, they were stacked in bundles of 200. These bundles were banded to facilitate handling. A double-end trim saw cut the studs to a final length of 92-5/8 inches. Next a tape-edge

banding machine removed splinters and roughness from the veneered edges. All of these operations were performed on standard production equipment at the particleboard plant in South Boston.

Figure 14.--Hot-stacking COM-PLY studs after they left the edge-bonding machine.

Every stud was then inspected. Any stud that crooked more than 1/4 inch, or bowed more than 3/4 inch, from a straight line was rejected. The veneer laminates were again examined for any defects that would decrease the strength and stiffness of the studs. The cores of the studs were examined for breaks, chipped edges, or other defects. Studs with any apparent delaminations between core and veneer, or between veneers, were rejected.

After the inspections, the studs were bundled into packages of 100 (fig. 15). These packages were stored at the South Boston plant until they could be shipped to the construction sites of the demonstration houses.

TESTING BOND QUALITY

During factory lamination, researchers took a representative sample of COM-PLY studs from daily production. Sixty of these sample studs were taken to the Forestry Sciences Laboratory in Athens, Georgia; of these, 20 were randomly selected for testing the quality of adhesive bonds. On 120 lap-shear specimens taken from these 20 studs, researchers determined the quality of the bonds between veneers. These specimens were tested in shear by tension loading after vacuum-pressure soaking in water. The test procedures are described in more detail by Vick (in press). Requirements for passing this test are equivalent to those specified in commercial standards for exterior-type, softwood plywood (APA 1974). The minimum requirement was that wood failure as opposed to adhesion failure average 85 percent in the tension-loaded specimens. Among the 120 specimens taken from the COM-PLY studs, the overall average for wood failure was 93 percent. Only 16 specimens had wood failure less than 85 percent.

Figure 15.--Packages of studs ready for shipment to building sites.

Researchers also tested the quality of the adhesive bonds between the veneer laminates and particleboard cores. The first of these tests determined the resistance of the bondlines to delamination after cyclic soaking and drying. The researchers believed that the amount of resistance to delamination would be the most reliable predictor of performance during exterior exposure. The maximum allowable delamination on production-run studs was 10 percent--the same as that allowed for daily production-runs of laminated lumber for exterior use by the American Institute of Timber Construction (1963). Thirty 6-inch-long

cross-sections cut from the random sample of 20 studs were tested for delamination. After two cycles of vacuum-pressure soaking and drying, average delamination was 1.0 percent. Only one of the 30 specimens had more than 10-percent delamination.

In the second test of the bonds between the veneer laminates and the cores, dry shear strength and wood failure were measured on 120 block-shear specimens from the random sample of 20 COM-PLY studs. Minimum average dry shear strength of the bonds was set at 500 lb/in^2. In the test specimens, dry shear strength averaged 652 lb/in^2. Only 18 of the specimens had shear strengths less than 500 lb/in^2. Minimum average wood failure for bonds made on the production line was set at 70 percent (AITC 1963). In the test specimens, overall wood failure averaged 71 percent--just over the minimum requirement.

CONCLUSIONS

The pilot operation demonstrated that it is technically feasible to laminate COM-PLY studs with commercial adhesives on a production line by using a continuously fed edge-bonding machine. With proper equipment for spreading the adhesive, this machine can be a fast and efficient means of producing acceptable bondlines in COM-PLY studs.

Although the bondlines made on the production line were somewhat weaker than those made under carefully controlled conditions in the laboratory, average values for the former exceeded the minimum requirements established for COM-PLY studs. Lower quality of the bonds in production-run studs was probably caused by precuring of the adhesive and variable pressure on the bondlines during the curing. These conditions were undoubtedly caused by the need to start and stop the edge-bonding machine each time a new batch of studs was fed into the machine. By synchronizing adhesive spreading with the continuous flow of the edge-bonding machine, it should be possible to produce stronger bonds at a much faster rate than in the pilot manufacturing operation.

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A simple and economically feasible method of laminating COM-PLY skins for use as wall framing in houses was successfully demonstrated in a pilot manufacturing operation. Researchers used commercial particleboard and veneer with a commercial phenol-resorcinol-formaldehyde resin adhesive in using steam heat in a continuously fed, edge banding machine. The bondlines in these skins met the minimum performance requirements for strength and exterior durability in COM-PLY skins.

KEYWORDS: Composite lumber, sandwich construction, phenolic particleboard, veneer, pilot manufacturing operation, bondlines, shear strength.

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Management of Eastern Hardwood Forests for Multiple Benefits (DYNAST-MB)

by

Stephen G. Boyce

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Management of Eastern Hardwood Forests for Multiple Benefits (DYNAST-MB)

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Abstract.--A new technique is described to harmonize forest management actions for multiple benefits, to give all interested parties an opportunity to participate in the selection of biologically possible combinations of benefits, and to provide alternatives for management previously not available. No one benefit is given preference over others, and no benefits are arbitrarily treated as constraints to the production of others. Structure of the technique is cybernetic--it is guided toward a goal by feedback processes.

Keywords: Multiple benefit, silviculture, forest management, system dynamics, cybernetics, timber, wildlife.

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1. INTRODUCTION

1.1 The Problem and a Solution

Passage of the National Forest Management Act of 1976 (90 Stat. 2949; 16USC1600) has increased the demand to manage forests for multiple benefits. The range of benefits now being consciously considered has expanded beyond the traditional economic values of timber and mineral production to include game populations, habitat for other animals and plants, water quality and flow, the beauty of the landscape, and many others. We know a good deal about how to manage for these individual benefits, but our attempts to match an increasing variety of benefits with an increasing variety of management techniques are leading to conflicting actions on the same piece of land.

The problem is to order and interrelate, harmoniously, the multiple actions of management which aim at producing multiple benefits from the forest. Often, two or three benefits can be matched one-to-one with an equal number of management actions. However, when many benefits are considered, the complexities of designing a whole management system become enormous. How to harmonize management actions to yield a desired combination of multiple benefits is perhaps the most puzzling and intractable problem for forestry in this century.

Computer modeling is a useful technique for dealing with a problem of this kind. A dynamic model can juggle a large number of variables, monitor the changing of quantities through time, and sense and respond to changes through feedback mechanisms. It can serve as a simulator to test the effects of different policies or as a guide for applying a chosen policy. The technique seems suitable for immediate practical application to forest management, a field in which cause-and-effect relationships are fairly well understood and the consequences of management actions are predictable within reasonable limits. Thus, a sound model of a managed forest would be not merely a tissue of systemized conjecture, but a practical tool, though of course it would be subject to revision through theoretical criticism and comparison with experience.

This report describes a system for managing the forest by actions harmonized to produce multiple benefits. The system is cybernetic in that it is guided toward a goal by feedback processes. It is based on a computer model of the managed forest, in which the hypothetical harvest of timber is regulated to guide the model toward an equilibrium of age classes yielding a constant annual flow of harvested timber and other benefits. This model is adapted from industrial dynamics (Forrester 1961, 1968) and uses the notations for the DYNAMO compiler (Pugh 1976). The system for forest management is cybernetic also in that the model will be constantly modified by the feedback of comparison with observed results in the forest.

1.2 An Overview of the Presentation

The first three chapters of this report explain the nature and function of the management system for a general readership, and are particularly aimed at forest managers who may be interested in applying it. The remainder of this introductory chapter will discuss the relation between the physical organization of the forest and the benefits which the forest produces; it will go on to show how a computer model can be used to predict and evaluate the consequences of various patterns of management. Chapter 2 describes in a nonmathematical way how the model traces the changing physical organization of the forest and extrapolates benefits. Chapter 3 explains how the system would be applied in the management of a real forest and discusses the roles of managers, researchers, and field foresters in implementing it.

The remainder of the report is directed toward readers with various specialized or theoretical interests. Chapter 4 discusses the structure of the biological systems from the standpoint of theoretical ecology; it presents four bionomic theories which underpin and validate the structure for forest management. Chapter 5 is a mathematical description of the core model for forest succession and harvest, with equations and a complete flow diagram. Chapter 6 gives details on the 17 algorithms which have been constructed to estimate benefits from eastern hardwood forests. In chapter 7, the printouts for six model runs are analyzed; these project the benefits resulting from six patterns of timber harvest for a specific area of Appalachian forest. The appendices list abbreviations, definitions, and equations used in the current version of the model.

1.3 DYNAST-MB

The system is named DYNAST, an acronym for "Dynamically Analytic Silviculture Technique." DYNAST consists of three complementary models adapted to different management purposes. The timber model, DYNAST-TM, harmonizes management actions for the production of timber. The optimum benefit model, DYNAST-OB, optimizes a specified benefit such as wilderness experience, recreation, visual appeal, habitat for a specific animal or plant, timber, water, or energy production. The multiple benefit model, DYNAST-MB, harmonizes forest management for multiple benefits. DYNAST-MB is the subject of this report; the other models will be described in later publications.

A model is a representation of some aspect of reality. All decisions and actions are based on models, which may be mental (a plan for a day's activities), physical (a floor plan for a building), or mathematical. Simple descriptive models can be envisioned without extensive documentation. When models become too large to be envisioned in their totality at one time, computers can be used to link large numbers of mathematical equations and to display the interrelationships as charts, diagrams, and tables. The computer and the mathematical equations are tools that organize and display parts of models in the same way a pencil is used to display a sentence on paper.

DYNAST is a system dynamics model that is different from descriptive models in several important ways. First, the theory of feedback systems is used to relate the information available from mental models and thus form a cybernetic structure. Second, four bionomic theories, which are mental models, are used to organize information to reflect changes in the forests being managed. Third, information that would otherwise stay in verbal, descriptive form is converted to an explicit display of interrelationships which can be used for making management decisions. This means that all the assumptions, which are derived from scientific research and experience, become quantitative and are displayed in interactive relationships in the same way that they occur in the forest.

The purpose of DYNAST-MB is to guide the management of the forest toward the production of whatever possible combination of benefits its managers choose. The model's structure does not prefer one benefit over another, nor does it treat one benefit as arbitrarily constraining another. DYNAST-MB allows us to assess an infinite number of management alternatives by predicting how each policy would affect timber production, habitat for a number of animal species, sediment flow, and the esthetics of the landscape. It can enhance human decisionmaking and help forest managers to balance values in response to conflicting demands.

1.4 A Preview of the Solution

1.4.1 The Relation of Benefits to Habitats

Each kind of forest community provides a different combination of benefits for man. For example, a stand of old growth offers den trees for bear and mast for squirrels, but little browse for deer; undisturbed, the old-growth stand minimizes sediment flow into streams but also minimizes the annual runoff of water. Other types of forest community produce other benefits, and a mixture of types within a limited area would yield yet another combination of benefits.

The important point is that the benefits available from a given forest depend primarily on the proportion and physical distribution of what may be called "habitats," differing forest communities dominated by particular age classes.

Before the advent of forest management, the distribution of habitats in a forest was shaped by wildfire, diseases, insects, the forces of weather, and human disturbances. These disturbances frequently created openings large enough to permit the growth of seedlings, which were followed, in time, by a succession of age classes. In a managed forest, however, the distribution of habitats is under human control. Regulated removal of trees makes openings which establish the future succession of communities. Because the distribution of habitats is, in the long run, controllable, and because forest benefits may be estimated for a given distribution of habitats, the way is clear for systematic management for multiple benefits.

Once supplied with coefficients for a particular locale, the DYNAST-MB model predicts the eventual distribution of habitats that results from a given pattern of timber harvest and predicts the resulting combination of benefits. DYNAST guides the model forest toward a steady state, an equilibrium in which the distribution of habitats remains constant; it also reveals how long the forest would take to reach equilibrium and what benefits would be available in the interim.

Using these model runs, forest managers can explore the consequences of many patterns of harvest, here called "modes of management." First, managers can preview the biologically possible combinations of benefits available for the locale. Second, they can choose the mode of management which leads to the most desirable combination of benefits. Finally, they can apply the chosen mode of management by selling timber at the rate specified by the model for each year, choosing tracts of an age and area compatible with the mode of management.

1.4.2 The Classification of Habitats

Since the system is based on the relationship between forest benefits and habitats, or types of forest community, a practical classification of habitats must be made for the area under study. The continuum of succession must be divided into classes that are significant for the benefits being considered. The classification will vary for different types of forest and can be modified whenever a new relationship is discovered between a particular age class and a particular benefit. The examples of modeling presented in this report use the following classification of the Appalachian hardwood forest:

Seedling habitats.--Stands with half of the dominant and codominant trees less than 1-inch d.b.h. (2.5 cm). A few scattered large trees are admitted.

Sapling habitats.--Stands with half of the dominant and codominant trees between 1 and 5 inches d.b.h. (2.5 to 12.4 cm). A few scattered large trees are admitted.

Pole habitats.--Stands with half of the dominant and codominant trees between 6 and 11 inches d.b.h. (12.5 to 27.7 cm). Pole habitats are classified by 2-inch (5 cm) diameter classes as pole-6, pole-8, and pole-10 habitats.

Mature timber habitats.--Stands with half of the dominant and codominant trees between 11 and 16 inches d.b.h. (27.8 to 40.6 cm).

Old-growth habitats.--Stands with half of the dominant and codominant trees larger than 16 inches d.b.h. (40.7 cm).

1.4.3 The Mode of Management

DYNAST-MB projects the distribution of these habitats resulting from different patterns of harvest, or modes of management. Three variables compose a mode of management: the fraction of the forest which is to rotate through the old-growth stage, as opposed to being harvested as younger mature timber; the ages of harvest for old-growth timber and mature timber; and the size of openings created when timber is removed.

Some old-growth timber is needed in an area being managed for a wide range of benefits. Old growth furnishes superior habitat for many kinds of wildlife, it has obvious esthetic value, and, when finally harvested, it yields large saw logs which are essential for certain uses. On the other hand, a tract which is cut as young mature timber will produce, in the long run, more timber than a tract allowed to rotate through the old-growth stage. Therefore, DYNAST distinguishes two fractions of the forest, one to be harvested as old growth, and one as mature timber. Note that these fractions represent the proportion of area being rotated through old-growth or mature timber rather than the area covered by standing old-growth or mature timber. (In the sample model runs, the coverage of old growth at equilibrium ranged around 70 percent of the designated old-growth fraction.) Any ratio of the two fractions may be entered into a model run as part of the definition of the mode of management. Designating particular areas of the real forest for old-growth rotation is a responsibility of management, which, carefully exercised, can increase the productivity of the forest. A tract can be rotated through old growth one time and mature timber another time.

The second variable defining the mode of management is the age for harvest of old-growth and mature timber. For a given area, the model is supplied with the average age at which a stand of trees will become mature or old-growth timber; however, a tract does not have to be harvested in the year it matures. To maintain a substantial coverage of mature and old-growth forest, necessary for many forest benefits, acreage may be left for some years in the mature or old-growth stage. The time delay between maturity and harvest becomes another option for management, and the model can help evaluate the effects of the delay. For example, delaying the harvest of old growth for a long time might so increase the benefits to wildlife (by increasing the actual coverage of standing old growth) that the old-growth fraction could be reduced, thus increasing the actual timber harvest while maintaining wildlife populations.

The size of openings is the third variable in the mode of management. Large openings lead to efficient harvest of timber, because fewer roads and skid trails are needed in proportion to the volume of timber removed. However, small openings are probably desirable esthetically, and they may aid wildlife by concentrating a variety of habitats within a relatively small area. Furthermore, some wildlife species benefit most from openings of a certain size range. The model can be programed for a mean opening size and an acceptable range of deviation from the mean.

1.4.4 Evaluating Modes of Management

The combinations of these three variables (old-growth fraction, age at harvest, and size of opening) yield a very large number of modes of management. Any of the possible modes may be simulated with the computer model to see what distribution of habitats it will lead to in equilibrium and what combination of benefits will follow. A series of trial screenings will help to define the biologically possible combinations of benefits and aid in the selection of a mode of management.

This section presents an example of trial screenings to show, in simplified form, how the model can be used to study the relationship between patterns of harvest and future benefits. A more detailed presentation of the same example may be found in chapter 7.

A tract of 6,396 acres of representative Appalachian hardwood forest in the Big Ivy watershed of Buncombe County, North Carolina, is modeled for the example. Since the area has been recently inventoried, there is reliable information about the current distribution of habitats for this area.

Of the enormous number of possible modes of management, three are illustrated here (six are presented in chapter 7). Two of these represent extremes: a "fast" mode which nearly optimizes timber harvest and a "salvage" mode which allows trees to grow to great age before removal (table 1). Coefficients for the salvage mode are to permit 99 percent of the area to succeed through the old-growth stage, to harvest old growth at about 300 years, and to limit openings to about 1 acre. For the fast mode, 99 percent of the area is harvested at about 86 years as mature timber, and harvest openings average 25 acres. The fast and salvage modes represent extremes within the possibilities for multiple-benefit management. Among the many possible intermediate modes, one called "moderate" is presented here for illustration. This mode permits 30 percent of the area to succeed through old-growth habitats harvested at about 200 years in openings averaging 10 acres; the 70-percent mature-timber fraction is cut at age 95 in openings of about 20 acres.

Any forest benefit that can be quantitatively related to the distribution of habitats may be modeled with DYNAST-MB. The current version of the system estimates 17 separate benefits and "impacts," or undesirable consequences, for the different patterns of management. The present introductory example plots seven benefits and one impact. The benefits are timber production and habitat for six animal species; the undesirable consequence is the flow of sediment. All these effects are scaled from 0 to 1 to allow easy comparison. For a benefit, the value 1 represents the maximum sustainable production--the amount produced if management favored that benefit above all others. For an impact, 1 represents the defined undesirable limit, beyond which an increase would be judged intolerable.

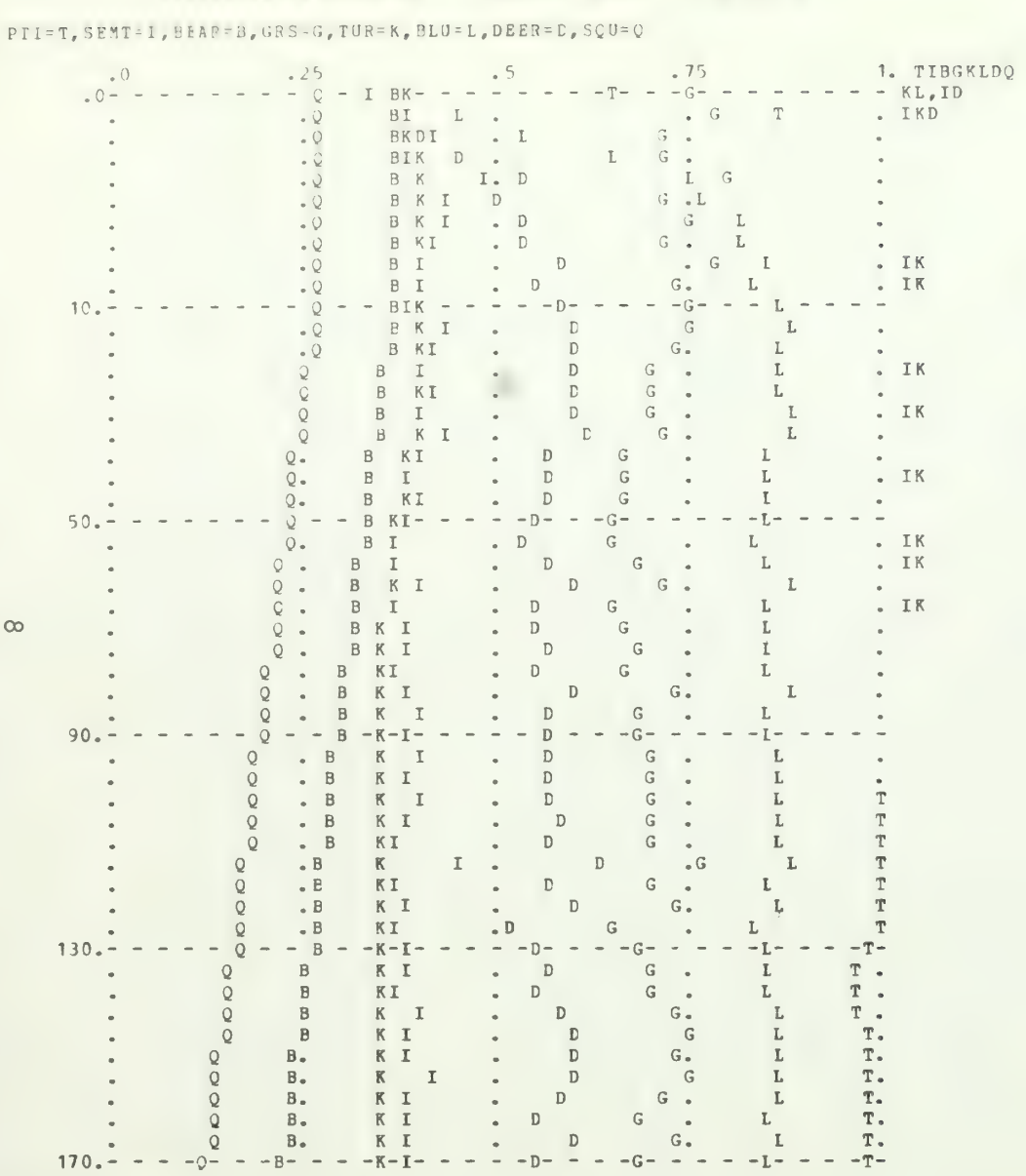
Table 1.--The control constants for six selected examples of modes of management

Kind of control constant[1/]	Rates of harvest					
	Fast	Basic	Moderate	Slow	Very slow	Salvage
Old-growth fraction (OGF, percent of total area)	0.01	0.1	0.3	0.5	0.7	0.99
Delay of mature timber habitat (DMT, years)	1	10	10	10	15	15
Delay of old-growth habitat (DOG, years)	1	65	105	155	200	200
Size of opening, mature timber (ISOM, acres)	45	25	20	10	5	1
Variance in opening size for mature timber divided by 2.4 (ISDM, acres)	2	1	1	1	0.3	0.2
Size of opening, old-growth habitat (ISOG, acres)	10	10	10	5	1	1
Variance in opening size for old growth divided by 2.4 (ISDO, acres)	1	1	1	0.3	0.2	0.2

[1/] Detailed descriptions are in section 3.5 and the appendix.

Figures 1, 2, and 3 plot the estimated consequences for the three modes of management (fast, moderate, and salvage) applied to the Big Ivy acreage. For the first 40 to 100 years, there is considerable change in the benefits produced because the distribution of habitats is changing. This transitional period varies from one mode of management to another in the example, and would be still different for another tract of forest with a different initial distribution. However, the model will eventually reach a balance of habitats which, with the particular mode of management, can be sustained for long periods, possibly hundreds of years. This steady state will produce a constant flow of benefits in a combination that is characteristic of the given mode of management.

Managers can examine the biologically possible combinations of forest benefits estimated by model runs for different modes of management and evaluate the trade-offs. In the introductory example, the fast mode yields near the maximum for timber production and bluebird habitat, but it offers poor conditions for gray squirrel and black bear; the salvage mode is low for all benefits except squirrel habitat. On the other hand, the moderate mode yields fairly high values for all of the benefits. The curves for sedimentation may seem to contradict common sense in that,



Legend for figures 1, 2, and 3, which show indices for seven benefits and one impact for three modes of management. T = potential timber index; I = sediment; B = bear habitat; D = deer habitat; Q = squirrel habitat; L = bluebird habitat; G = grouse habitat; K = turkey habitat. Indices are plotted annually for the first 10 years, then at 3-year intervals. Letter groups at the top of the graph indicate coincident indices; the first letter of each group appears on the plot.

Figure 1.--Fast mode.

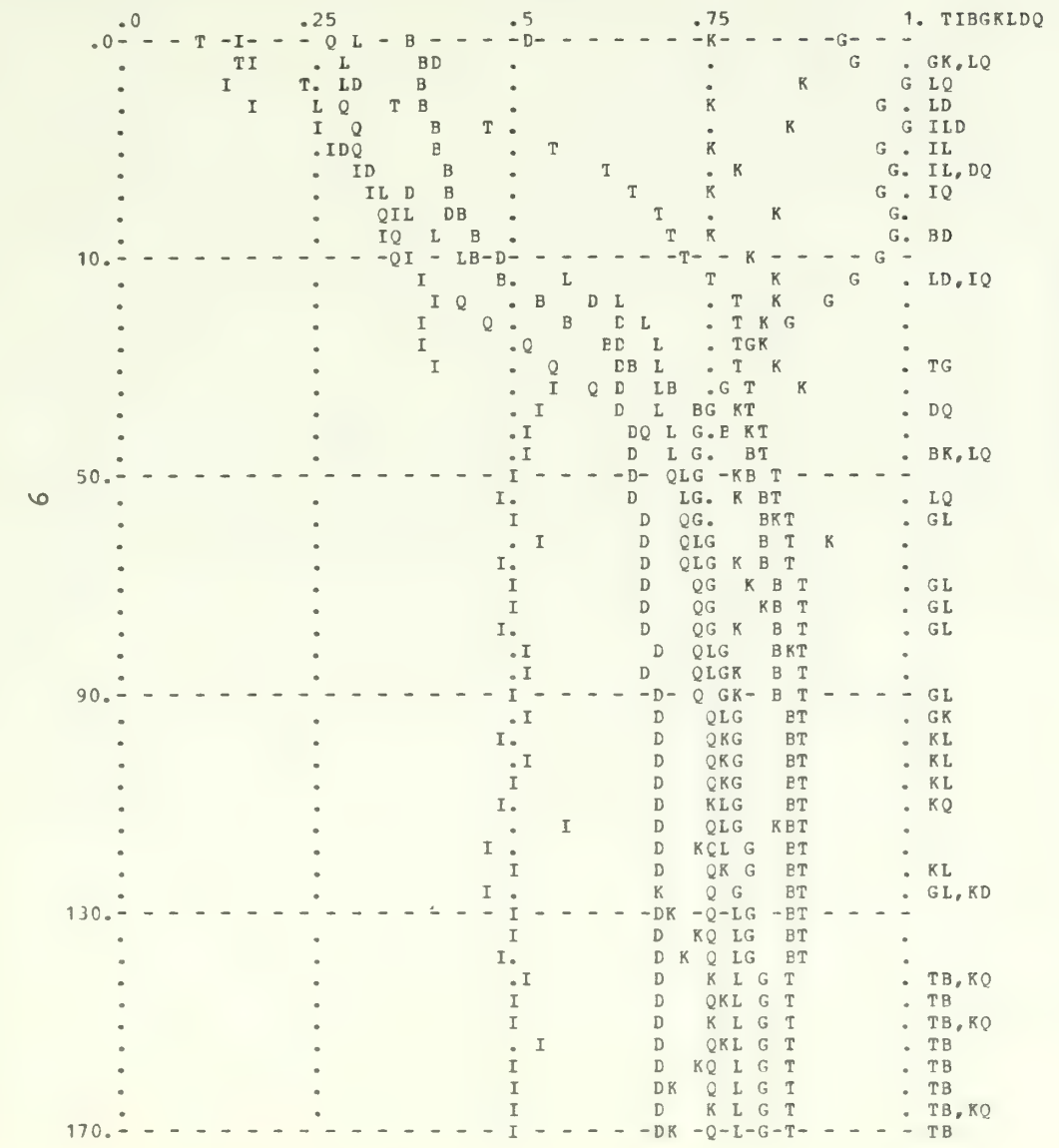


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Figure 2.--Moderate mode.

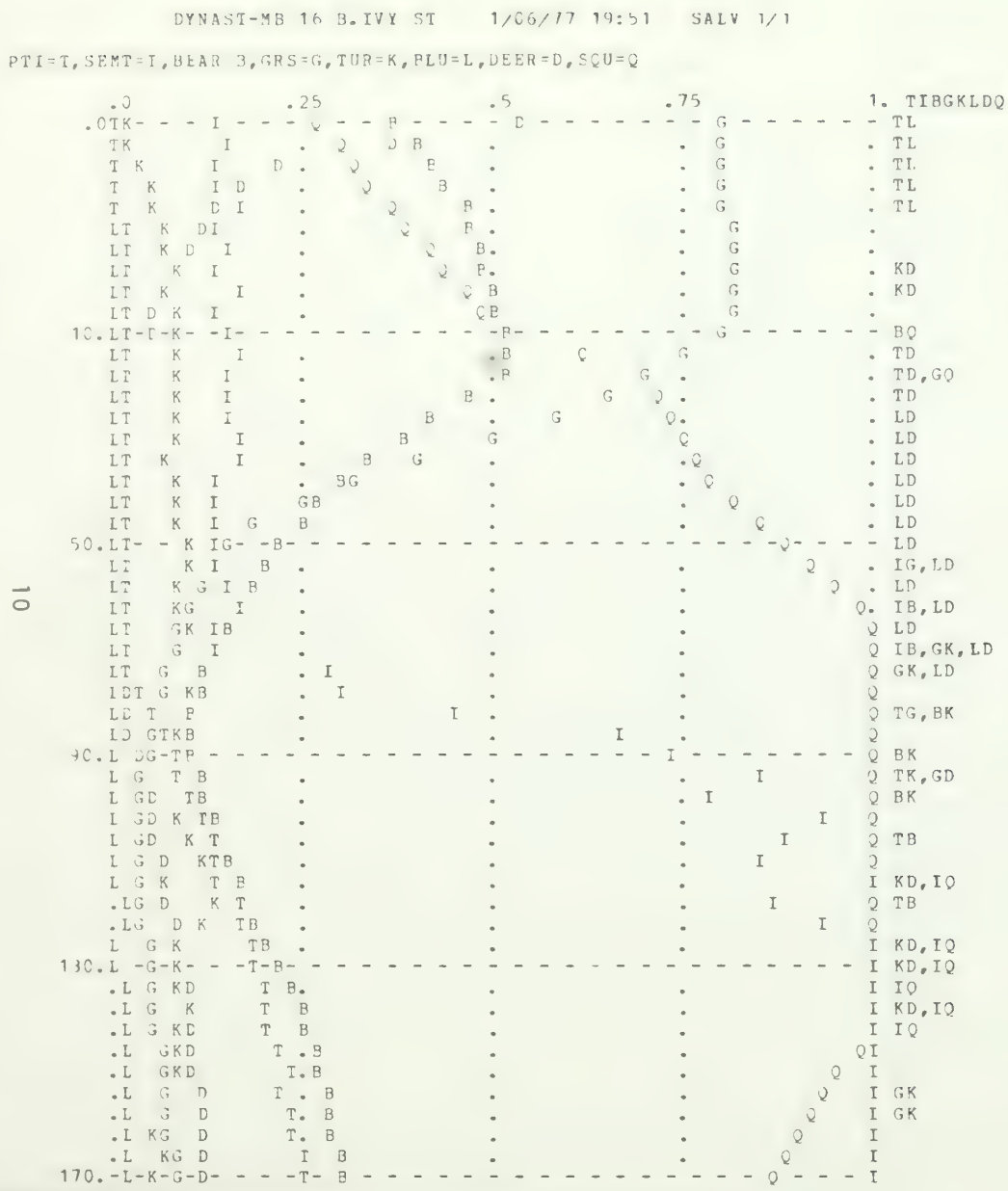

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Figure 3.--Salvage mode.

at equilibrium, the very conservative salvage mode produces the highest flows of sediment. The very small openings allowed by the salvage mode cause this effect by requiring a great deal of road construction, which is the most important cause of sediment flow.

These are only three of an infinite number of modes of management. The variables of old-growth fraction, age at harvest, and size of opening can be manipulated in trial screenings to produce other combinations of benefits. If very old trees are desirable for esthetic or other reasons, but sedimentation needs to be reduced, then a mode resembling the salvage but with larger openings could be tested, and the model will show the expected combination of benefits with a reduced flow of sediment. If timber production gets a high priority, the model can test various fast and intermediate modes and show with some precision what loss in wildlife habitat follows from a given increase in timber harvest. Once a mode of management is selected, numerical values can be printed out to guide the application of the mode or to provide more detailed information (table 2).

The point is that DYNAST-MB makes the trade-offs explicit so that managers and other interested parties who participate in the choice of a mode of management can understand the consequences to the extent allowed by the current state of knowledge about forestry. Management decisions would not be turned over to the computer and its keepers; rather, the decisionmaking process could become more open and more responsive to the needs of society than ever before.

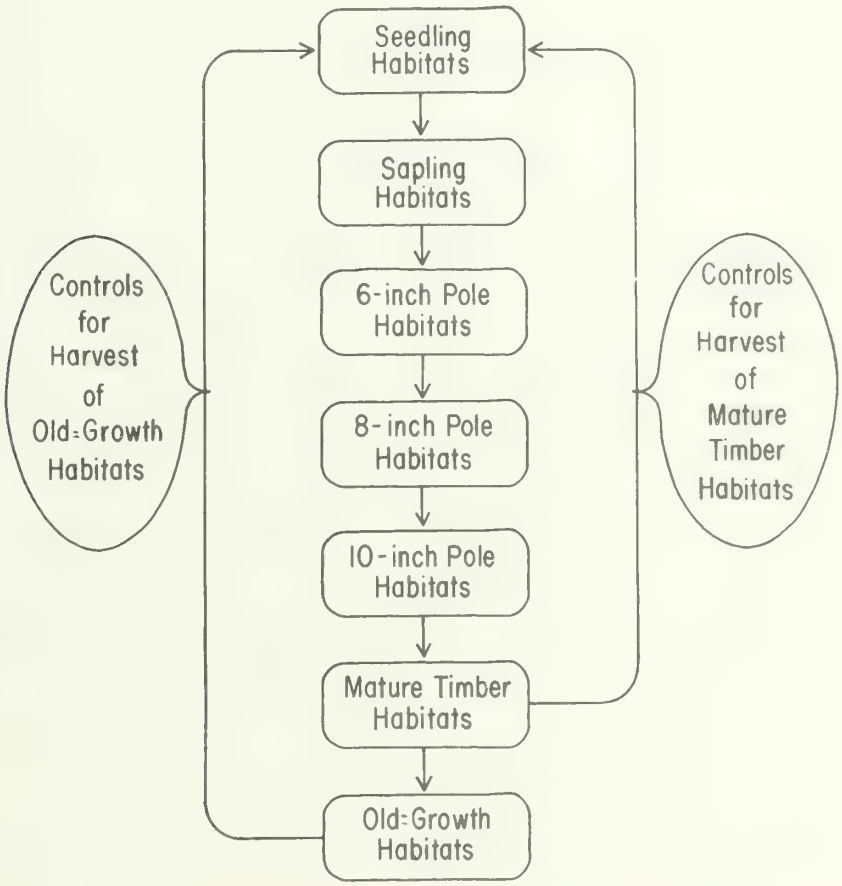

Figure 4.--A simplification of the DYNAST-MB model. The cybernetic structure for management converts the open system for community organization to a closed system. Negative feedback loops have the goal of maintaining a certain distribution of habitats.

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TIME	OGS VOG	MTS VMT	PTI VT	OG MT	P1 P8	P6 SA	SE SEMT	DEER SQU	TUR GRS
E+00	E+00 E+03	E+00 E+03	E+00 E+03	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00
.0	.0000 .000	13.691 28.21	.09525 28.21	185.0 379.7	1808.0 740.0	1843.0 1254.0	200.00 .14326	.52237 .27355	.74622 .90959
1.	.0000 .000	24.963 42.52	.14355 42.52	188.7 457.3	1769.5 809.7	1763.9 1249.9	170.75 .15982	.39378 .27701	.92800 .92956
2.	.0000 .000	33.867 71.48	.24136 71.48	194.5 525.0	1737.2 869.9	1689.7 1240.9	152.43 .13868	.29242 .28244	.86608 .99738
3.	.0000 .000	40.887 104.11	.35154 104.11	201.9 582.3	1710.2 921.5	1620.1 1229.4	144.33 .17412	.25333 .28944	.74717 .97453
4.	.0000 .000	46.411 135.78	.45847 135.78	210.7 629.6	1687.7 965.3	1554.6 1217.4	144.55 .25097	.25729 .29766	.85443 .99241
5.	.0000 .000	47.511 163.37	.55160 163.37	220.3 668.4	1668.9 1002.0	1492.9 1206.2	150.91 .26869	.28145 .30665	.74373 .97395
6.	.0000 .000	47.940 181.69	.61349 181.69	230.0 701.3	1653.4 1032.5	1435.0 1197.0	160.54 .30832	.32413 .31575	.78150 .98025
7.	.0000 .000	48.347 193.58	.65362 193.58	239.8 730.4	1640.5 1057.3	1380.5 1190.1	171.19 .31537	.36846 .32494	.74387 .97398
8.	.0000 .000	48.737 201.62	.68077 201.62	249.7 756.8	1629.6 1077.0	1329.3 1185.5	181.66 .35762	.41743 .33420	.83396 .98899
9.	.0000 .000	49.110 207.35	.70012 207.35	259.6 781.3	1620.5 1092.2	1281.4 1183.1	191.39 .33787	.45551 .34353	.75235 .97539
10.	.0000 .000	49.469 211.69	.71476 211.69	269.6 804.5	1612.8 1103.4	1236.6 1182.7	200.16 .36114	.48399 .35294	.80294 .97070
50.	3.3649 14.937	49.460 231.99	.83374 246.93	686.4 1277.4	1260.5 790.6	714.9 1419.4	260.23 .49437	.64967 .70732	.79088 .73351
90.	7.2874 36.026	47.992 222.36	.87243 258.38	900.6 1128.5	1028.5 746.7	761.5 1568.6	274.95 .50258	.67551 .74081	.77650 .77045
130.	8.7397 43.952	47.448 211.23	.86160 255.18	979.9 865.1	1035.7 793.7	809.6 1644.9	280.40 .49308	.68211 .75321	.70571 .79791
170.	9.2775 46.901	47.247 204.96	.85039 251.86	1009.3 698.8	1081.0 825.4	833.5 1678.7	282.42 .49551	.68636 .75780	.69704 .81521

Table 2.--The moderate mode with 20-acre openings for mature timber and 10-acre openings for old growth (MODR 20/10). Data for the control of timber sales and information about the distribution of habitats and the indices of benefits. OGS = old-growth sales (acres/year); MTS = mature timber sales (acres/year); VOG = removals of old-growth timber (cubic feet/year); VMT = removals of mature timber (cubic feet/year); PTI = potential timber index; VT = volume of total timber removed (cubic feet/year); SE, SA, P6, P8, P1, MT, and OG = area of seven habitats (acres); SEMT, DEER, SQU, TUR, GRS = indices respectively for sediment, deer, squirrel, turkey, and grouse. The scales, E + 03, at the top of the table, indicate the timber volumes are to be multiplied by 10^3.

2. THE DYNAST-MB MODEL

2.1 Modeling Succession and Harvest

The core of the DYNAST-MB system is a dynamic model of the changing distribution of habitats (age classes) in the forest as modified by the harvest of timber. The model has a cybernetic structure; it is arranged to guide the forest toward a goal through a set of negative feedback loops. The goal is to achieve a given distribution of habitats and maintain it in a steady state, thereby producing a constant flow of benefits in the desired combination. The feedback mechanisms control the removal of timber to create a steady flow of acreage into seedling habitat, thus regulating the proportions of different habitats in the forest of the future.

Figure 4 presents a simplified version of the DYNAST-MB model. This diagram suppresses time delays, accounting processes, and certain feedback mechanisms regulating the flow of succession into the old-growth state. The complete model is described mathematically in chapter 5.

The central sector of the model monitors the flow of succession through the classes of habitat. Time delays for each stage of growth must be fed in for the area under study. (For example, in the Southern Appalachians, 5 years are allowed for the transition from seedling to sapling habitat.) The model can then project the distribution of habitats for any point in the future and estimate the combination of benefits the forest will yield. More importantly for the structure of the system, the model senses the current distribution of habitats and, through its feedback loops, makes adjustments to guide the managed forest toward the desired equilibrium.

The left side of the diagram shows the old-growth feedback loop. The removal of old growth is regulated by the availability of old growth of suitable age and the area of old growth desired. That is, if the old-growth timber now standing is much less than the amount desired at equilibrium, the removal of old growth is retarded on a sliding scale; if the old growth exceeds the desired proportion, its removal is accelerated. When the steady state is reached, the harvest of old growth is equated to the flow of acreage into the old-growth stage.

On the right side of the diagram is the mature-timber feedback loop. Several mechanisms regulate the sale of mature timber. There is an adjustment for desired mature timber coverage parallel to the one for old growth. The need for mature timber coverage is balanced, in the model's equations, against the need for new seedling areas to shape the distribution of habitats for the future. Eventually, the sum of these decisions creates an equilibrium which can be sustained almost indefinitely.

When DYNAST is used to predict the consequences of a given mode of management, it simply computes the indicated rates of harvest for each year and integrates them into its projection of the future state of the model forest. When the system is being used to guide the management of a real forest, managers would read out the indicated sale of old-growth and mature timber and select tracts for harvest during the year. However, since the modeling process can never be perfect, inventories and controls must be continuously used to keep the model forest in touch with the real forest and with the goals of management. In the core model, the time delays in the flow of succession and in the practical harvesting process must be compared with experience; in the algorithms for estimating benefits, the relationships must be continuously

updated by the findings of researchers; and in the overall choice of a combination of benefits or a mode of management, the changing needs of society may modify the policies chosen in the past. Ultimately, human needs and human knowledge guide the management of the forest.

2.2 Estimating Benefits

The DYNAST core model predicts what distribution of habitats, or age classes, will follow from a given mode of management. This part of the system is applicable to many, perhaps to all, types of forest, needing only to be supplied with growth rates (successional delays) for the locale or perhaps with a different classification of habitats than the seven that were chosen for the eastern hardwood forests. However, the part of the model that estimates benefits is specific for a given type of forest.

The availability of benefits depends on the state of physical organization of the forest--the proportions which are covered by seedlings, saplings, pole timber, mature timber, and old growth. Algorithms, or statements of relationship, must be constructed to express how a particular benefit depends on the distribution of habitats. The current version of DYNAST-MB incorporates 17 algorithms for estimating benefits in eastern hardwood forests. The algorithms are written as nonlinear supplementary equations. An algorithm may be added, deleted, or changed without affecting the core model or the other algorithms; thus, this part of the structure is quite flexible and may be readily adapted to different circumstances or modified by new knowledge from research or inventories.

The particular relationships assumed between habitats and benefits must always be regarded as tentative and subject to revision. For a start, we can derive a set of algorithms from current practical and scientific knowledge of forestry and forest ecology. As the system is applied, these assumed relationships would be tested by measuring the production of benefits in the real forest, and they would be adjusted to fit a particular area. New algorithms could be added as changing social needs focus interest on a different set of benefits; for example, an algorithm could be constructed for an endangered species. The model is a dynamic management structure through which new knowledge from research and experience can be used to improve decisionmaking.

The following sections offer a general explanation of some of the algorithms now used in DYNAST-MB. For the equations and a fuller explanation of how the algorithms were derived, see chapter 6. For the scaling of indices, see section 1.4.4.

2.2.1 Timber

The algorithms for timber production yield a potential timber index, which is the ratio of the volume predicted for harvest to the volume that would be expected if timber production were favored over all other benefits. For the Appalachians, a rotation of 80 years is assumed to produce the maximum yield of sawtimber. The model estimates productivity under an 80-year rotation and compares it with productivity for a given mode of management, with its specified old-growth fraction, ages of harvest, and size of openings. The algorithm includes a factor which reduces estimated yield where small openings are required, because cutting timber in a small area causes

disproportionate damage to surrounding trees and because the growth of young trees is slow in a small opening. Published studies of timber volume per acre for the different age classes supply data for the computation.

2.2.2 Wildlife

The model incorporates algorithms for the major game species of Appalachian forests and for several other arbitrarily chosen, but representative, species. In each case, the algorithm states a relationship between the distribution of age classes in the forest and the species' habitat requirements. For example, the index for white-tailed deer has a high value when many small areas of seedling habitat are dispersed in an area which also has substantial stands of large pole and mature timber. Seedling habitat contributes soft mast and forage, while 10-inch pole timber and mature timber are the most bountiful producers of hard mast for winter food. The deer index rises toward the maximum of 1 as seedling habitat increases up to 7 percent of the total area and as mast-producing habitats increase to 20 percent of the area; these are assumed to be optimal proportions within the practical limitations of multiple-benefit management. Deer can probably use seedling browse more effectively when it occurs in small, well-dispersed openings; therefore, the deer index rises as opening size diminishes toward 6 acres. Beyond these limits, assumed to be optimal, the contribution of a factor to the index levels off; in the model, 1-acre openings are no better for deer than 6-acre openings. In similar fashion, algorithms relate the requirements or preferences of other animals to the distribution of habitats in the forest.

Wildlife researchers have established the general habitat requirements for many species, and data from published research underlie all the algorithms described in chapter 6. However, many of the quantified relationships, especially the optimal proportions of different habitats and the optimal size of openings, are based on fragmentary or inconclusive data and will need to be revised in the light of future research. Indeed, one of the virtues of the DYNAST system is that it provides controlled conditions for studying the relation of wildlife populations to different forest habitats. In turn, the system is refined by the research which it helps to foster.

2.2.3 Sediment Flow

Particles of sediment flow through the landscape at varying rates, affected by the steepness of slopes, wind, the movement of water above and below ground, and the kinds of geologic substrate. Forests retard the flow. The flow rates of both organic and inorganic particles are delayed by the matrix of roots and soil and by the protective cover of leaves, branches, and other litter. Trees can be removed from the forest with relatively small increases in the flow of sediment if the protective layer of litter and the surface matrix of roots and soil are not destroyed. Road building, which breaks up the surface layer, is the most important cause of increased sediment flow.

A practical index of sedimentation can be based on the number of openings formed per square mile of forest per year. The number of openings is an index of the number of miles of roads and skid trails required to remove the timber (Nyland and others 1976). As the size of openings decreases, the number of openings for equal areas of harvest increases. However, where there are many small openings, the miles of roads and skid trails required per opening may be reduced by clustering the openings. Thus, the relationship between the openings per square mile and the silt production is not a straight line; as the number of openings increases, sedimentation increases, but at a declining rate (fig. 5).

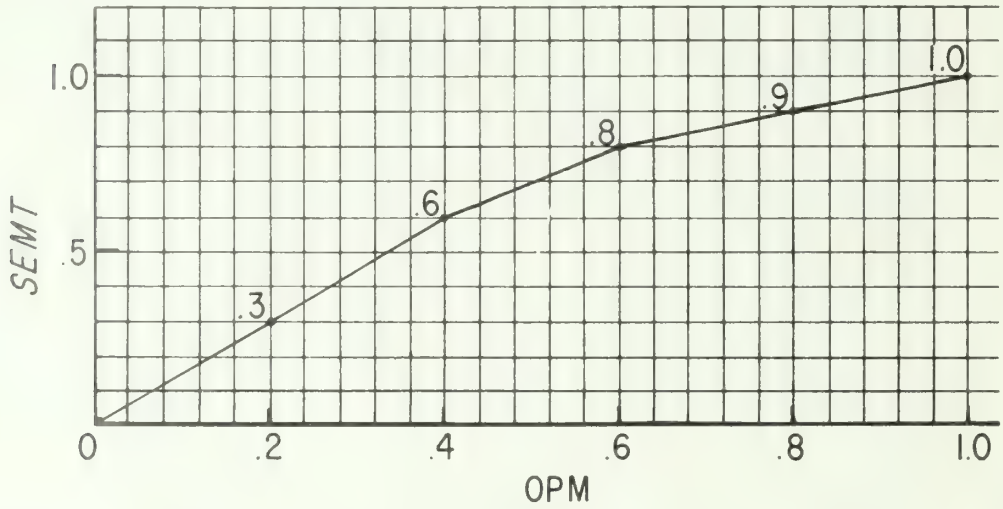

Figure 5.--The indicated flow of sediment (SEMT) versus the number of openings formed per square mile of forest (OPM).

For typical modes of management, the number of openings per square mile normally varies between 0.2 and 0.6. The unacceptable limit of 1 on the index scale is reached when one new opening per square mile per year is formed, while an index of 0 indicates that no openings are being formed. Although considered "unacceptable" for management purposes, the movement of sediment at the index value of 1 is still much smaller than losses from most other kinds of land use (U. S. Environ. Prot. Agency 1973; Oertel 1974).

2.2.4 Esthetics

Trying to measure the beauty or ugliness of a landscape may be a fruitless enterprise, and certainly the normative judgment implied in scaling an esthetic index from 0 to 1 can reflect, at best, only a consensus of subjectivities. However, because the appearance of a forest is certainly related to its distribution of age classes, some elements of forest esthetics may be quantified and modeled. DYNAST-MB incorporates algorithms for "ugliness" and "visual variety."

The raw, disorderly appearance of recently harvested timberland is the subject of the ugliness index. This index integrates the total area in seedling habitat, the frequency of openings, and the size of openings. As any of these increases, the ugliness index increases. The unacceptable limits which define a value of 1 are a 6-percent fraction of seedling habitat, opening size averaging 30 acres, and openings formed at the rate of one per square mile per year.

Variety and contrast are important criteria for assessing the visual appeal of a forest environment (Larson 1971; Zube and others 1975). Within the topography of any landscape, the distribution of forest stands of contrasting heights can affect visual appeal. The index for visual variety distinguishes three height classes: young stands under 50 feet, mature and pole timber stands over 50 feet, and tall, flat-topped old-growth stands. The index rises toward the maximum of 1 when these classes are in balance, each occupying 30 to 40 percent of the total area, and when seedling habitat is at the minimum (4 percent) required to maintain the balance of the three size classes in the future.

2.2.5 Other Algorithms

The model also includes algorithms for gray squirrel, turkey, ruffed grouse, and black bear habitat; for four woodpeckers; and for four songbirds, bluebird, towhee, ovenbird, and pewee, which represent groups of birds with different habitat requirements. There is no algorithm for water volume or for nutrient flow. Hydrological research for the Appalachians suggests that normal modes of multiple-benefit management will not materially affect the annual runoff of water, and we simply do not know enough at this time to be able to model the flows of nutrients with any precision. A nutrient index remains a possibility for the future, however, and it would be important in relating patterns of timber harvest to the long-term fertility of the forest environment and to the nutrients entering streams. These questions are explored in chapter 6.

3. APPLYING THE DYNAST-MB SYSTEM

To apply the DYNAST system, managers would first screen a series of modes of management for their estimated benefits and impacts. The model is prepared for the trial screenings by providing it with successional delays for the area under study and with definitions of several modes of management. If the algorithms for estimating benefits which are described in this report are unsuitable for the purpose, new algorithms may be constructed and inserted. After the trial runs are evaluated, further screenings of intermediate modes of management may be tried until a mode of management is found which produces the most desirable combination of benefits.

Once a mode of management is chosen, it is applied by selecting areas for harvest at the annual rate indicated by the tables for the model run (table 2). The choice of areas for old-growth rotation and sites for openings will need to be made carefully, with consideration of the local topography. After the systematic management of a real forest is underway, frequent inventories and continuous research will be needed to adjust the modeling process to the dynamics of the real forest.

3.1 The Choice of a Mode of Management

The modes of management are determined by seven kinds of constants that are listed in table 1. The first three constants (OGF, DMT, and DOG) determine the rates of timber harvest. The remaining four constants (ISOM, ISDM, ISOG, and ISDO) determine the average size and variance of openings desired.

The constant OGF determines the proportion of the area that is to rotate through the old-growth habitat. The remaining area is rotated through the mature timber habitat.

The constant DMT determines how long mature timber habitat is to be kept in this state after it becomes mature timber. Typically, this delay would be only 1 to 15 years. Normally the period should not exceed 35 years, since many of the dominant and codominant trees would begin to exceed 16 inches d.b.h. and should then be considered as old-growth habitat. The sum of DMT and the age for transition to mature timber (AMT), age 85 in the example, is the approximate age for harvest of mature timber at the steady-state distribution of habitats.

The constant DOG determines how long the old-growth habitat is to be kept in this state after it becomes old growth. The transition age to old growth (AOG) is the sum of the transition age to mature timber (AMT) and the delay of mature timber (DMT). AOG plus DOG yields the harvest age for old growth. DOG may be made as long as 200 years. The effects of longer delays cannot be modeled accurately, because there is little information about the behavior of such old stands. The sum of DOG and the age for transition to old growth (AOG) is the approximate age for harvest of old growth at the steady-state distribution of habitats.

The number of possible modes of management is very large. For example, if we consider five different values for each of five constants (OGF, DMT, DOG, ISOM, ISOG), the number of modes for consideration is

5^5 = 3,125. This enormous variety can be reduced by examining extremes and a sample of intermediate modes. An initial combination of six modes is suggested in table 1 and chapter 7. After examining the combinations of benefits and impacts from these modes, one may want to examine a few other modes. The process of trial and examination continues until a mode is found that provides the most desirable combination of benefits and impacts. One may use any desired name for the modes; those used in table 1 suggest the rates of timber harvest.

Procedures for improving the precision of management decisions for a given area and for adapting the DYNAST system to a different area or different kind of forest are similar and will be described together.

The DYNAST system is relatively easy to use and to adapt to areas different from the example. The amount of information required for the first period of operation is minimal. During successive periods, repeated adjustments improve precision until the management system is adapted to a specific area of land. This is the essential information required for the first period of operation:

--An accurate inventory of the distribution of habitats.

--Information about the rate of succession and the reliability of natural regeneration after harvest.

--A set of algorithms which relate benefits to the distribution of habitats and the sizes of openings formed by harvesting.

3.2 Inventories and Management Decisions

The first step is to obtain an accurate inventory of the area covered by each type of habitat. Inventories by age class (5-year increments) or by size class (1- or 2-inch increments) may be converted into the classification defined in section 1.4.2. If data are not already available, some kind of inventory method must be used (Husch, Miller, and Beers 1972). Permanent control plots, if obscurely marked so they will not receive special consideration, are probably most effective over a long period of time.

Inventories should be repeated at the intervals, possibly 10 years, that keep differences between the model and the forest within acceptable limits. One use of repeated inventories is to adjust the control constants (sec. 1.4.3) and to change the coefficients for delays in succession in the model. Second, the inventories provide information essential for evaluating the performance of the management system. Information for management decisions should not be confused with the validation of algorithms for estimating amounts of benefits (sec. 3.5) nor with evaluating in-place decisions (sec. 3.7). Inventories should be totally independent of any information collected for use in assessment of benefits and impacts and any information used to make in-place enhancements.

To maintain this distinction, these inventories for management information and decisionmaking should be the responsibility of an inventory unit of central management (Beer 1966). These inventories should be limited to collecting information needed to evaluate and refine the functioning of the core model: the delays for succession, the rotation age for maximum timber production, the model's running estimate of the proportionate distribution of habitats, and the coefficients defining the mode of management. For an

example of the use of these constants, see the C-cards listed at the end of the list of equations in appendix A and the C-type definitions listed in appendix B. The essential information is given in the following equations:

```
DSE=5/DSA=30/DP6=15/DP8=15/DP1=20                                    106.4, C
TMR=80                                                               106.5, C
ISE=200/ISA=1254/IP6=1843/IP8=740/IP1=1808/IMT=366/                  106.6, C
  IOG=185
DMT=1/DOG=1/OGF=.01                                                  106.7, C
ISOM=45/ISDM=2/ISOG=10/ISDO=1                                        106.8, C
```

DSE - DELAY FOR SEEDLING SUCCESSION (YEARS)
DSA - DELAY FOR SAPLING SUCCESSION (YEARS)
DP6 - DELAY FOR POLE-6 SUCCESSION (YEARS)
DP8 - DELAY FOR POLE-8 SUCCESSION (YEARS)
DP1 - DELAY FOR POLE-10 SUCCESSION (YEARS)
TMR - TIMBER MAXIMUM ROTATION AGE (YEARS)
ISE - INVENTORY SEEDLINGS (AREA)
ISA - INVENTORY SAPLINGS (AREA)
IP6 - INVENTORY POLE-6 (AREA)
IP8 - INVENTORY POLE-8 (AREA)
IP1 - INVENTORY POLE-10 (AREA)
IMT - INVENTORY MATURE TIMBER (AREA)
IOG - INVENTORY OLD GROWTH (AREA)
DMT - DELAY FOR MATURE HABITAT SUCCESSION (YEARS)
DOG - DELAY FOR OLD GROWTH SUCCESSION (YEARS)
OGF - FRACTION REMOVED THROUGH OLD GROWTH HABITAT (PERCENT)
ISOM - DESIRED AVERAGE SIZE OF OPENING MATURE HABITAT (AREA)
ISDM - DESIRED STANDARD DEVIATION OPENINGS MATURE HABITAT (AREA)
ISOG - DESIRED AVERAGE SIZE OF OPENING OLD GROWTH (AREA)
ISDO - DESIRED STANDARD DEVIATION OPENINGS OLD GROWTH (AREA)

3.3 Delays for the Flow of Succession

The delays for successional change must be estimated from historic data. For the Appalachians, the most extensive information comes from Schnur (1937), the unpublished reports of Frothingham,[1] reviews of research, and data from the Forest Survey (Knight, in press). These data are used to develop the relationship of age to median diameters at the junctures for classes of habitats (fig. 6). The average delays for successional change are initially determined from this relationship. For the Appalachians, the average delay for seedling habitats is 5 years. On some areas the time may be 6 to 7 years, and on other areas it may be as low as 3 years. The successional delays for sapling habitats are 30 years; for pole-6 and pole-8 habitats, 15 years each; for pole-10 habitats, 20 years. The total time required to grow mature timber is 85 years.

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[1] Frothingham, E. H. 1917. Report on study of cut-over areas in the Southern Appalachians. Unpubl. Mimeogr. 229 p.

These constants are used to model the successional change from harvested areas to mature timber habitats. Errors in these constants for a specific area are to be corrected with information from each successive inventory.

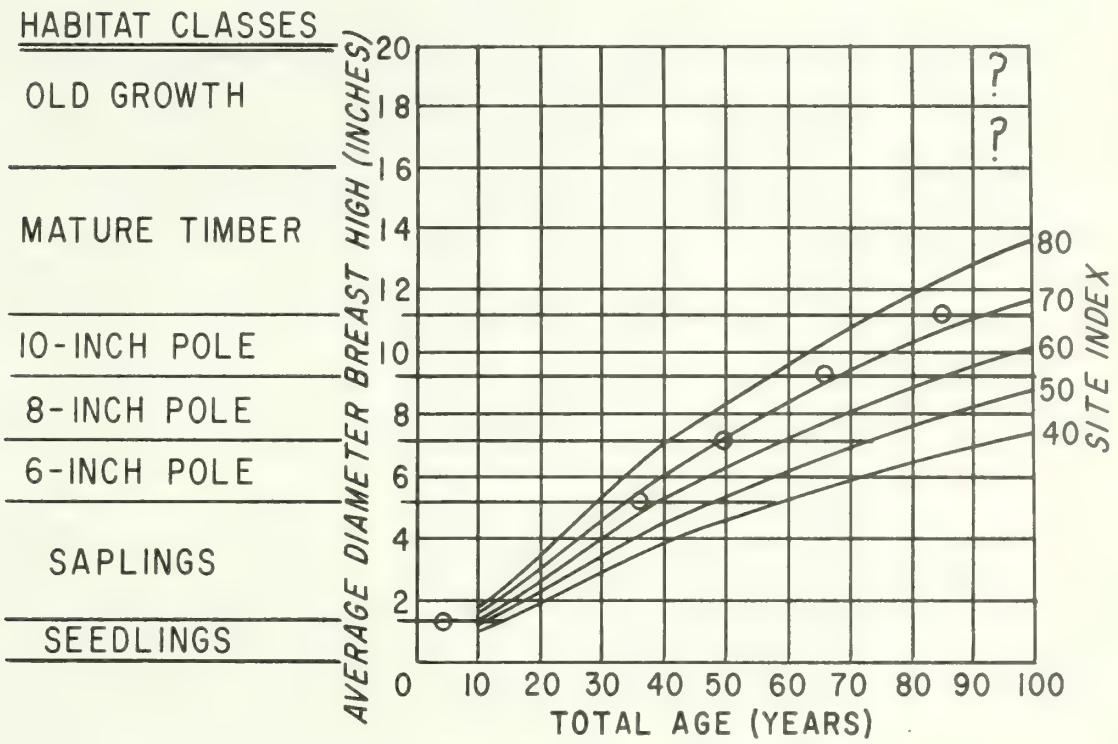


Figure 6.--The relation of habitat classes to age. (Modified from figure 6, Schnur 1937.)

3.4 Development of Algorithms for Benefits

From the theory for multiple benefits (sec. 4.5), the proportional distribution of habitats determines the kinds and proportions of multiple benefits available from the forest. At any given moment, in the model run, the relative amount of a particular benefit is estimated by algorithms. These are written as supplementary equations to the model for management. The algorithms are independent of each other. They do not influence the core model for succession and harvest, and they are totally dependent on the distribution of habitats and the size of openings.

Information for developing algorithms is derived from research and experience. The turkey index will illustrate the method for building an algorithm. From research and experience, a list was made of all the forest states of organization that are important for turkey habitat. A long list of habitat requirements is given in the Wildlife Habitat Management Handbook, chapter 401 (U. S. Dep. Agric., For. Serv. 1971). Because the enormous variety of items listed could not possibly be controlled by management actions on millions of acres (Ashby 1960; Beer 1966, 1972), the least important items and those that cannot be directed were removed from the list. The items that remained were those important indicators of turkey habitat which are affected by patterns of timber harvest.

For the turkey index, this analytical process resulted in the selection of hard mast, forage, soft mast, seeds, insects, snails, and cover. All of these variables can be expressed by two forest conditions: the size and distribution of openings and the proportion of area in mast-producing forests. From the Wildlife Habitat Management Handbook, chapter 200 (USDA FS 1971), hard mast is most abundant in stands averaging 8 to 16 inches in diameter. With this information a curve can be drawn on a piece of graph paper (fig. 7) that expresses this assumption: as the proportion of area in hard-mast-producing habitats increases, the quality of habitat for turkey increases. But there is a limit to how much of the forest can be kept in pole and mature timber when the distribution of habitats is brought to a steady state. A few calculations showed that only about half of the forest can be maintained in these states at equilibrium; this is a biological limit. The optimum quality of turkey habitat was set at this limit (fig. 7). The turkey habitat index is 1 when half of the forest is producing hard mast and 0 when none of the forest is producing hard mast. The next step was to determine the shape of the curve between 0 and 0.5. This curve must be based on experience, on whatever can be found in publications, and on the biological constraints when the forest is at different steady states. The shape of the curve will later be refined by periodic assessments and validations (sec. 3.5).

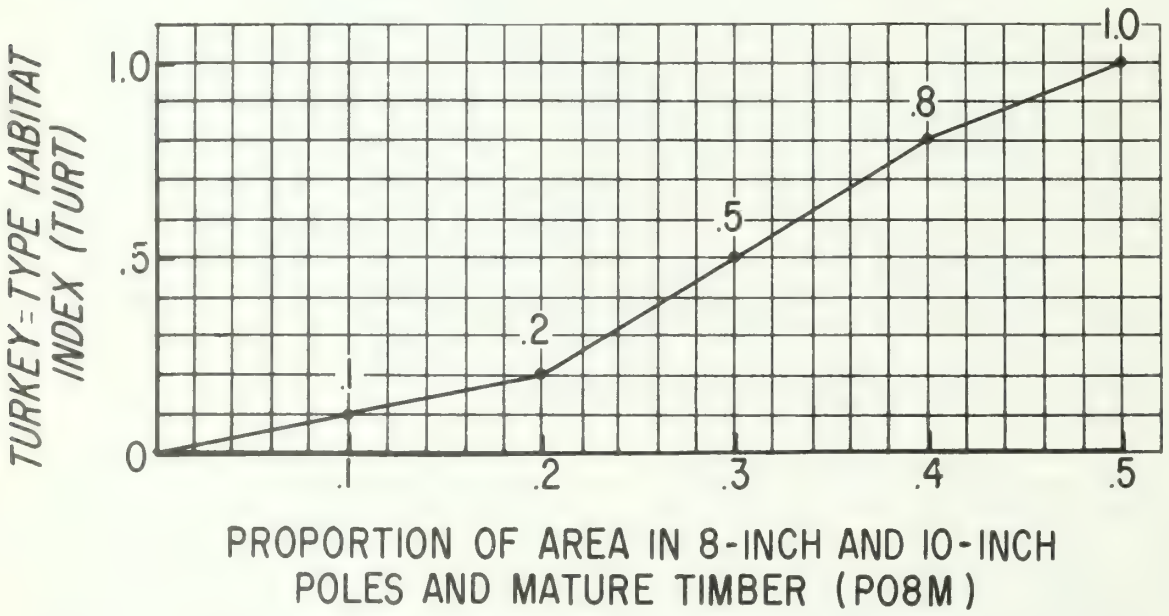


Figure 7.--Turkey-type habitat index versus the proportion of area in 8-inch and 10-inch poles and mature timber.

A second component of the index is the type of opening. (For any mode of management, the size and frequency of openings are computed as supplementary information by equation number 50, sec. 5.3.) In the index for opening type for turkey, the assumption was: both very small and very large openings have low value for turkeys. Some range of opening sizes must represent an acceptable quality of habitat for turkeys. This assumption was expressed as a graph (fig. 8). When the size of openings is less than 10 or greater than 16, the index for turkey opening type declines. Finally, the indices for mast and openings are multiplied together. The result of this analysis is an index that indicates the quality of turkey habitats as the organization of the forest changes.

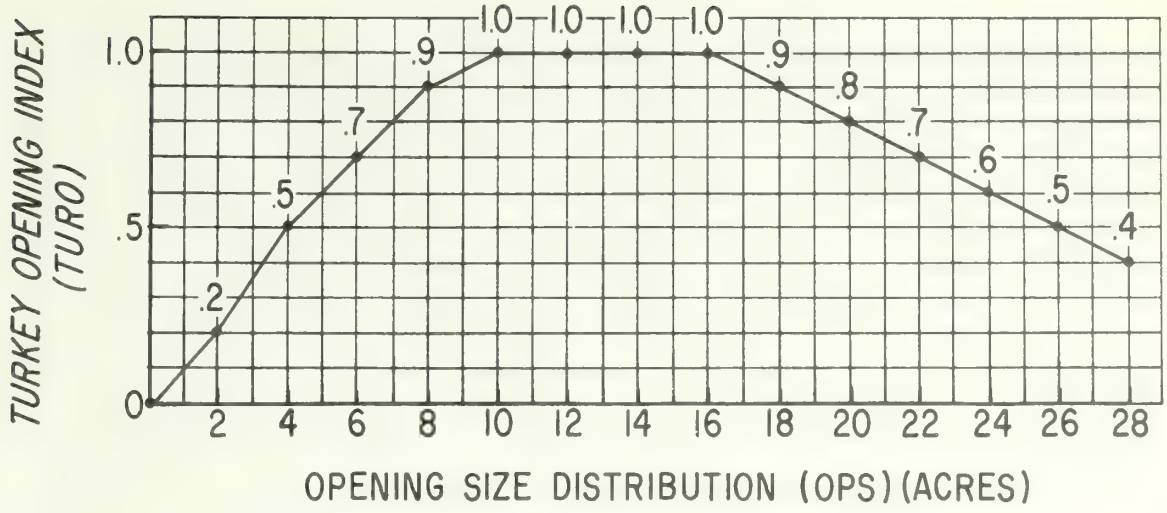


Figure 8.--Turkey opening index versus the distribution of size of openings (OPS).

It is not necessary to be concerned with how much area is in sapling stands, which provide cover, because this state will always be satisfied whenever the turkey index is relatively high. The same is true for soft mast, seeds, insects, and snails. Another limitation not covered by the turkey index is the need to distribute seedling habitats by removing some timber each year from every tract of about 600 to 1,000 acres. This is an example of an in-place decision (sec. 3.7).

A very large number of benefits and impacts may be expressed as algorithms; those of interest are the ones that provide a basis for selecting a management mode. Each algorithm may be adjusted with new experience and research data to reflect more closely the real forest. Again, adjustments in one algorithm do not affect other algorithms, because they are independent of each other.

3.5 Validating the Algorithms

Initially, algorithms are developed from information derived from research and experience. Later, they are assessed according to data collected from the real forest and then modified for a specific area. The assessments and the modification of the algorithms should be made by well-trained and experienced specialists and kept totally separate from the inventories (sec. 3.2). The purpose of the assessments is to develop algorithms that provide a rational basis for management decisions to modify the mode of management.

The algorithms are assumed relationships with parameters derived by statistical analysis from experimental data and experience. The statistical analyses are available in the scientific literature as fragments of the dynamic behavior of the forest.

There are several difficulties in deriving algorithms from published research: differences in biometric techniques, differences in results among studies, and the inability to relate research results to the states of forest organization. These difficulties can often be resolved by using

the relationships that closely fit the experience, observation, and descriptive knowledge of forest managers. In this way the validity of each algorithm is based on experimental evidence and tempered by practical experience. The system provides for changing the assumed relationships as new knowledge becomes available. The use of nonlinearity in the assumptions allows us to closely fit the relationships to the results of research and experience. A more detailed discussion of nonlinear relationships may be found in Wagner (1975, p. 525) and Forrester (1961).

Some aspects of the algorithms are more sensitive than others. Research aimed at validating or adjusting the algorithms should begin by focusing on these sensitive points. Again, the turkey habitat index serves as an example. From the assumption about opening size and frequency (fig. 8), it is readily apparent that, when opening size (OPS) is less than 8 acres, changes in OPS change the index rapidly; when openings are larger than 16 acres, the index is affected only moderately; and when openings are between 10 and 16 acres, the index is not affected by changes in OPS. Thus, as the algorithm has been constructed, the opening size range of 0-8 is most sensitive to change. When research undertakes to adjust the algorithm according to turkey production in a particular area, refining this sensitive sector of the curve will have the greatest effect on the output of the model.

An important point is that the validity of the algorithms for benefits and impacts will be determined by how well research and experience can continue to develop relationships and relate them to the states of organization of particular forests.

3.6 Starting the Model and Making Sensitivity Tests

The model is started by inserting appropriate control constants reflecting an inventory of the distribution of habitats in the area to be managed. This information is entered into the model as the constants ISE, ISA, IP6, IP8, IP1, IMT, and IOG (equation 106.6,C).

Then, values for rates of harvest (OGF, DOG, DMT) and for sizes of openings (ISOM $\pm$ ISDM and ISOG $\pm$ ISDO) are selected to provide a range of management modes for screening (table 1). The values for ISDM and ISDO are determined by choosing the maximum desired deviation from size of opening and dividing this value by 2.4, which is the limit in the normal deviate function (NORMRN) (equations 106.7-106.8).

The delays for succession (DSE, DSA, DP6, DP8, DP1) are derived from research and observation. They are changed only when there is reliable, new evidence to adjust the age and diameter relationship (sec. 3.3) for the specific area under management.

All control constants should have values of 0.0001 or greater. This precaution reduces the probability of an attempted division by zero.

TMR is the rotation age that maximizes the production of timber. It must be specified for the particular area under management (sec. 6.1). Typically, it is the age when mean annual increment peaks. This age varies according to whether one wishes to consider saw logs, pulpwood, or total cubic volume.

Once the model is supplied with control constants and successional delays for a particular area, tests should be run to determine the sensitivity of the model to the various changes. These tests have two functions: to identify any areas of weakness in the logical structure of the model, and to identify areas in which research needs to be concentrated.

One kind of sensitivity test is to make large changes in the control constants for the mode of management. If the resulting change in output seems unrealistic, or if the model becomes unstable, there may be an error in the structure of the model. Such errors can normally be corrected by referring to the diagram of the information network (fig. 9) and the list of equations (appendix A).

Another kind of test is to observe the effects of small changes in the delays for succession upon the modeled distribution of habitats and production of benefits. If the changes in output are large, this might conceivably reflect a defect in the model, but more likely calls attention to a real and important property of the biological system. For example, if reducing the delay for succession of seedling habitats from 5 to 3 years greatly affects the timber production and wildlife habitat, then research is urgently needed to determine the exact successional delay for seedling habitat in the area under study.

Thus, sensitivity tests serve not only to determine whether the model reflects the dynamics of the forest, but to help identify needs for specific assessments and research.

3.7 In-Place Enhancement of Habitats

Many cultural actions are opportunistic, in that they depend upon the state of the forest, the availability of investment funds, local markets, or demands for certain benefits. Some examples are thinning, pruning, leaving den trees, making water holes, locating trails, applying fertilizers, and weeding. Such measures, because they are planned by someone on the scene, are called "in-place." These actions cannot be easily predicted and are not incorporated into the model.

The results of any in-place enhancements should become readily apparent in the inventories of habitats and in the assessment of the algorithms. For example, if thinnings in pole stands speed the transition to mature timber habitats, this change should be apparent in the inventories; the algorithms for both potential timber index (PTI) and for volume of timber harvested (VT) would then be adjusted for the next inventory period.

One important in-place decision for game animals is to schedule annual timber removals within the range of mobility of the animals (USDA FS 1971). The dispersion of openings can be controlled to some extent by changes in the rates of harvest and sizes of openings, but someone who knows the area's topography must review the specific sites with this principle in mind.

3.8 Adapting DYNAST to Other Types of Forest

The DYNAST-MB program can be modified for use with almost any kind of forest. The following information is required: the delays for

succession of habitats; the extent that natural regeneration or artificial reforestation forms stands similar to those harvested; the ability to predict, at least for a few decades, the sequential states of community organization; and information to relate the production of benefits to the states of organization. This kind of information is provided in the literature for many kinds of forests. The most important consideration is to be able to predict the kind of regeneration that will be achieved after harvest. The problem is more difficult with artificially regenerated stands because of the uncertainty of economic, social, and other factors that determine the commitment of resources to artificial regeneration.

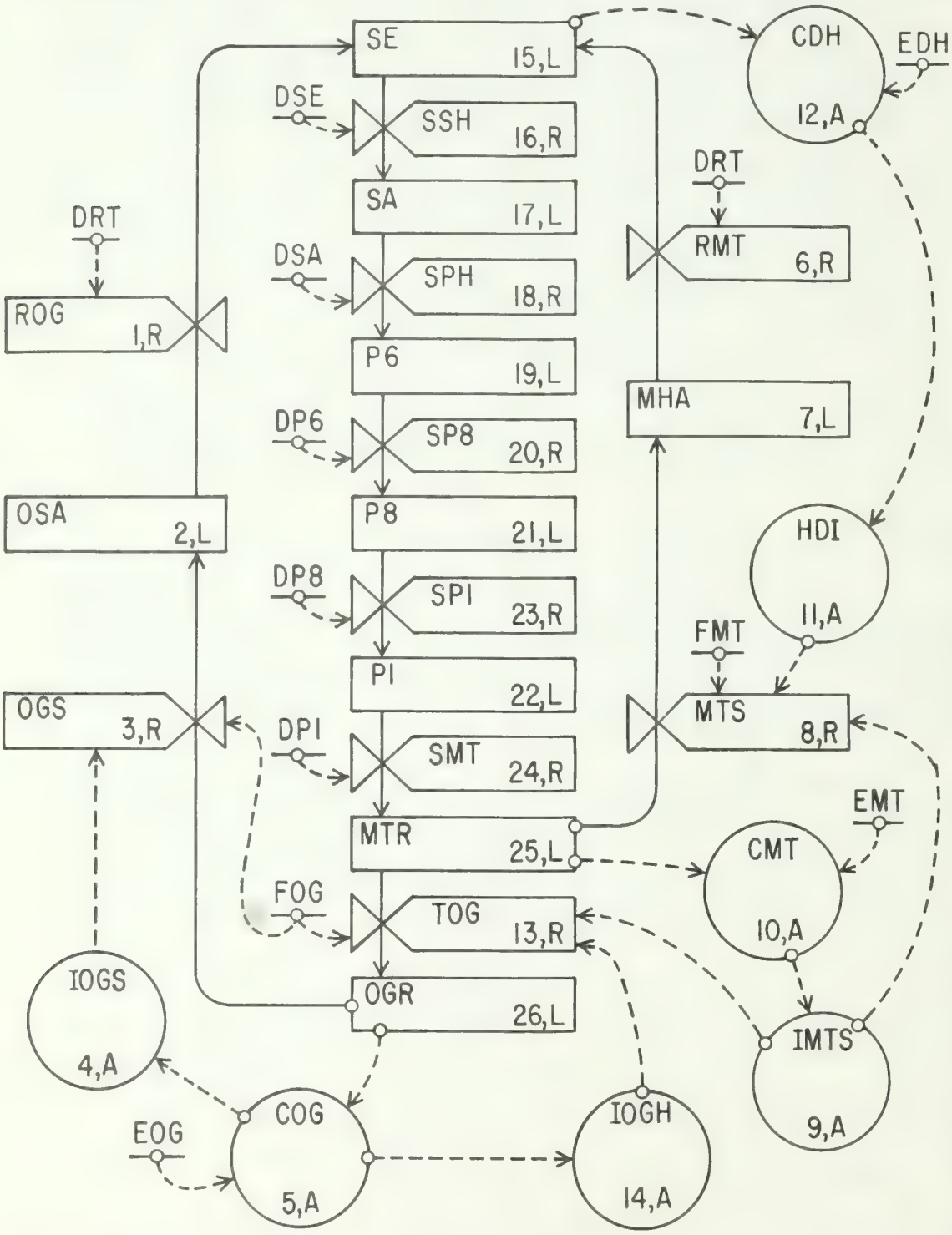


Figure 9.--Flow diagram of the information network for the DYNAST-MB model. Each equation is described in the text by number and type.

4. STRUCTURE OF THE BIOLOGICAL SYSTEMS

Obviously, a method of forest management must be compatible with the systems of the natural forest. This chapter presents four bionomic (ecological) theories that describe the cybernetic structure of the biological systems and that underlie the DYNAST structure for management.

4.1 Control and Communication

Control and communication in biological systems are possible because of structure--the way the component parts are connected. There are many kinds of structure; the type that is of interest here forms information feedback loops that direct the behavior of the system to achieve or maintain some goal, such as keeping the level of blood sugar within the limits for life. These are negative feedback loops with goals. A negative feedback process, as defined by Weiner (1948), is one in which a decisionmaking process regulates the system by comparing the present[2/] conditions with a standard or goal and making adjustments to achieve a steady state. Feedback loops make the system aware of its own performance, using outputs to regulate inputs. Algebraic signs can reverse in the decision process. If there is too much, a quantity will be reduced; if there is too little, it will be increased. When this kind of system is disturbed, it typically reacts with a series of diminishing oscillations which, by assimilating feedback, gradually home in on the goal, which typically is a steady state with minimum oscillations. A hand reaching for an object moves through such oscillations on a nearly invisible scale. These oscillations illustrate reversals of algebraic sign, by which a decision process alters states to approach the goal (Forrester 1968; Milsum 1966).

Other kinds of structure may have no feedback loops, or may have feedback which is positive rather than negative. Positive feedback loops, of which birth rate is an example, tend only in one direction and have no mechanism for reversing an algebraic sign. Systems with only positive feedback loops cannot take corrective action in pursuit of a goal or to maintain a standard. Without a goal, counteractions may achieve a sort of balance, as the interaction of death rate and birth rate may tend to maintain a population within some limits. However, a system without a goal does not move toward a predictable steady state. For example, the human population has not tended toward stability, but has increased steadily throughout its history with only minor downward fluctuations. If the population is to attain even an approximation of stability, it will come only when we establish a negative feedback process with goals. Or, in another sort of example, a population of predators and its prey may sometimes tend to influence each other's population. However, the dynamics of such a system, which does not have a population goal, do not show decreasing oscillations tending toward a steady state, but rather fluctuations that are totally unpredictable. A predator can decimate a prey population or even eliminate it; a prey population can outrun the predator's capacity to control it.

[2/] In mathematical analysis, there is no "present"; "immediate past" is technically more accurate.

A clock is a good example of a positive feedback system. Energy from the spring moves the hands forward, providing, as an output, the display of time. But the input is not affected by the output; the clock has no mechanism for sensing its own performance and taking corrective action in accordance with a goal. If the clock is running fast, it will deviate increasingly from the standard as time passes. Past states do not control future states, even though the states (positions of the hands) are repetitive. The clock becomes part of a negative feedback process when its owner adjusts the speed control device on its back. He compares the clock's performance with a standard and decides to take corrective action by retarding the speed control. Later, he evaluates the performance again and takes further action, probably making a smaller correction. The system oscillates and gradually reaches the goal.

Some biological systems use negative feedback processes with goals, and others do not; it is essential to recognize this difference. Four bionomic theories, defining the structure of forest systems, can help us to understand the dynamics of forests, both managed and unmanaged. The theories serve to interrelate empirical data and to reduce complexity. As a model of the dynamics of control and communication in a forest, the theories form the basis for a cybernetic structure for management.

For further information on control, communication, and the use of cybernetics in management, see Weiner (1948), Forrester (1961), Beer (1966), Milsum (1966), Klir (1969), and Ashby (1973).

4.2 The Theory for Individualistic Systems

Each living organism and its environment form an individualistic system with negative feedback loops guiding behavior in accordance with the goal of survival. Behavior is directed by decision mechanisms. These mechanisms are genetically and environmentally determined and are part of the physiological, anatomical, and morphological structure of the individualistic system. Each individualistic system senses and reacts to its own state and uses past or present states to influence future actions to achieve the goal of survival, as a tree grows toward the light.

This is not a new theory but a restatement, in very much condensed form, of the model of organisms developed by Darwin and modified by others (Tansley 1935; Machin 1964; Waddington 1970; Becht 1974). This theory is the foundation of the other three bionomic theories. The dynamic behavior of these individualistic, goal-seeking systems determines the organization of forest communities and the transformation of these communities from state to state. The individuality of these systems and their goal-seeking behavior cause every individualistic system to develop differently from every other individualistic system. Thus, in forestry, mortality of trees cannot be predicted except as a statistical probability for a population in some specified state of community organization. Nor is it possible to predict which seedlings, saplings, or other understory trees will become dominants with succeeding states of organization.

Mortality, like other forms of behavior, results from the dynamics of individualistic systems. Death occurs when a feedback loop fails to maintain one or more essential functions, such as respiration, circulation, food consumption, hydration, or physical integrity, within the limits

for survival. Failure in a feedback loop may result from changes in the environment or failure in the structure of the individualistic system. This mortality, resulting from the dynamics of individualistic systems, organizes survivors into forest communities.

The theory for individualistic systems would be falsified by discovery that any individualistic system's existence, mortality, or behavior is for the exclusive achievement of a goal for the forest community.

4.3 The Theory for Organization of Forest Communities

The mortality of individualistic systems organizes survivors into forest communities without goals. Large numbers of seeds and other propagules, which are individualistic systems, die by their own dynamics. This mortality organizes the survivors into successive states.

These successive states have dynamics similar to those of the clock previously described, but there is a major difference. Clock hands exactly repeat former states, whereas biological communities do not. If the genotypes and environments are similar to combinations in preceding forests, the kinds of succeeding individualistic systems will be similar to those of the preceding forest, but not identical. Thus, the successive states of organization only appear to be repetitive. These apparently repetitive states of organization are well known as "stages of succession."

Forest communities are organizationally unstable because the surviving individualistic systems are joined without community goals directing negative feedback loops. In the absence of such feedback loops, the community cannot sense its own state of organization and cannot use past states to influence future actions to achieve a goal for the community. The community has no decision mechanisms to direct the life, death, reproduction, and replacement of mortal individualistic systems. The forest community is an aggregation of survivors and no species is essential for community organization. For example, the loss of the American chestnut (Castanea dentata, Marsh., Borkh.) did not kill the forest as girdling would kill a tree. The chestnuts were replaced by other individualistic systems. Moreover, successive generations of individualistic systems are genetically and environmentally different from preceding generations. Mortal individualistic systems are replaced by different individualistic systems, not coming back around like a carousel (Moore 1975), but never again to be exactly repeated. In the absence of community sensing and decision mechanisms, forests continue through time without goals.

The theory for organization of forests would be falsified by discovery of a control and communication mechanism that senses the states of community organization, makes decisions, and directs the mortality and the behavior of organisms to achieve organizational goals for the forest community.

This theory for community organization means that forest communities without human intervention never come to a steady state of organization. In the words of Gaylord Simpson (1969), "If indeed the earth's ecosystems are tending toward long-range stabilization or static equilibrium, 3 billion years has been too short a time to reach that condition."

On the other hand, people can form systems with goals and with negative feedback loops that can bring the distribution of states of organization to equilibrium. Forest management then becomes a cybernetic structure that senses changes in the states of the forest and takes action to maintain the states of organization within the limits of some goal. To achieve this, the management system must be capable of using current information to make decisions about the future. Current information about the state of organization of a forest community can be used to predict the next state with acceptable accuracy for short periods of about 5 to 10 years. For example, during the next 10-year interval, an Appalachian pole stand with dominant trees averaging 6 inches in diameter will very likely transform to a stand with trees averaging about 8 inches in diameter. Predictions of the physical states of organization are more reliable than predictions of changes in species composition.

4.4 The Theory for Flows of Energy and Materials

The flows of energy, nutrients, carbon dioxide, oxygen, water, and organic materials are unidirectional and have the dynamics of systems without goals and without negative feedback loops. The flows of energy and materials through the landscape are delayed by the individualistic systems which compose the forests. Rates of flow are modified by changes in the states of community organization. Cycling is only an additional period of delay that is ultimately determined by the dynamics of individuals.

The theory would be falsified by discovery of sensing and decision mechanisms in the community that regulate the inflows, internal status, and outflows of energy and materials to achieve organizational goals for the forest community.

The significance of this theory is that the delays in flows of energy and materials are brought to a steady state when the distribution of states of community organization are brought to a steady state. There are a very large, if not an infinite, number of states of community organization and an equal number of combinations of flows of energy and materials. Perhaps an inventory of the states of community organization such as that supplied by the model can eventually be used to indicate the delays in flows of energy and materials. One application would be to estimate the flow of nutrients into streams; this would make possible an index for biological productivity of streams (see sec. 6.14).

4.5 The Theory for Multiple Benefits

The kinds and proportions of states of organization (habitats) determine the kinds and proportions of human benefits available from a forest. Many variables define the physical organization of a forest area: plant and animal species, age and size of the dominant plants, amount of shrubs and herbaceous plants, depth of the litter, volume of accumulated wood, amount and proportional distribution of nutrients, physical structure of the soil, biomass, and the flow of nutrients and water through the forest. Different combinations produce a very large variety of habitats, and a correspondingly large variety of potential human benefits, including scenic values, hunting, hiking, timber, streamflow, and places to live for plants and animals. It is the proportional distribution of kinds of habitats that provides a particular combination of benefits at a given time.

The theory for multiple benefits would be falsified by discovery that all potential benefits are simultaneously available from a single state of community organization.

The significance of this theory is that, if the distribution of habitats is kept at equilibrium, a particular combination of benefits will be produced in perpetuity; and there are as many patterns of benefits as there are patterns of physical organization.

4.6 Validation of the Bionomic Theories

Theories are typically validated by two methods (Popper 1959, 1962; Becht 1974). The simpler of the two methods is to state a critical hypothesis, which, if found to be true, would falsify the theory. Examples of such hypotheses are stated above for each of the bionomic theories. Until a critical hypothesis is found to be true, the four theories are not falsified and can serve as a basis for constructing a rational and useful forest management system.

The other method to determine the truth of the theories is to put them to practical uses which will confirm them or show them to be untrue. In forestry, this method requires a long time and a large number of observations. This method is incorporated into the management system through the periodic inventories. Statistical methods and empirical research will be used to evaluate the theories. Thus, the value of the theories and the management structure are examined by day-to-day experience as well as by specialized scientific and technological research. This interweaving of theory, statistical data, and practice is acknowledged to be helpful in applying technology effectively and improving management (Beer 1966).

None of the four theories is wholly new. They have been expressed in the biological literature or exploited in practice for many years. For example, the individuality of organisms is expressed by Tansley (1935), Gleason (1939), Waddington (1970), Becht (1974), and others. Foresters modify the organization of forest communities by changing the natural rates and kinds of mortality by weeding, thinning, removing cull trees, preparing regeneration sites, planting, and regulating the time of harvest. Delays in the flow of water, nutrients, energy, and other materials have been previously related to the states of forest organization (Smith 1962; Seaton 1973). The relation of states of forest organization to human benefits has been subjectively known for many years if not previously stated as a theory. This relationship has been the basis for modifying the habitats for game animals for hundreds of years. Thus, the theories are based on enormous amounts of information accumulated over many years by research and experience.

The uniqueness of the bionomic theories is that they are stated in terms of control and communication mechanisms for organisms and communities of organisms. The theories describe cybernetic relationships within and among organisms and thus provide the basis for a logical management system. The theories are called bionomic, a synonym for ecology.

5. A TECHNICAL REPORT ON THE DYNAST-MB MODEL

5.1 Bionomic Theory and the DYNAST Model

The bionomic theories suggest a management system set up to maintain a certain distribution of states of forest organization at a steady state in perpetuity. The natural organization process for forests results from mortality, is without goals, and occurs in sequential states. The sequence of states (habitats) is predictable for short periods of time. Combinations of habitats (Elton 1949; Andrewartha and Birch 1954) provide different combinations of benefits at a given time. The way to achieve a distribution of habitats is to regulate the diversion of older habitats to young habitats. If such diversions are regulated appropriately, habitats can be proportionately distributed to provide various combinations of multiple benefits in perpetuity. The goalless system for community organization is thus converted by management to a system with the goal of maintaining a certain distribution of habitats in a steady state.

5.2 The Core Model for Succession and Harvest

The model is a set of negative feedback loops with the goal of converting the current distribution of habitats to the desired distribution and maintaining the desired distribution at a steady state. This is achieved by using harvest rates for old-growth and mature timber to control formation of seedling habitats. Goals are established by assigning constants to the old-growth fraction (OGF), the delay of old-growth habitats (DOG), and the delay of mature timber habitats (DMT) (table 1).

Equations for computing the rates of harvest are written for the DYNAMO II simulation computer (Pugh 1976). This compiler is especially useful for revealing the systemic behavior of models with feedback loops and with integration equations (Forrester 1961, 1968). The relation of these equations to the model and the structure of the feedback loops is illustrated in a flow diagram of the information network (fig. 9). Arrows show the direction of flow of information. Solid lines indicate a flow of information about changes in the inventory resulting from the harvest of timber and the succession of habitats. Dashed lines indicate a flow of information about the state of the inventory and other parts of the system. Rectangles display stocks, or accumulations of information about the state of the system. The states are computed by level equations identified by "L." Diagrams of "valves" indicate rate equations (R) that describe the changes in the system for each interval of computation. Changes in the rates in relation to other parts of the model are made clear by making some of the rate calculations in auxiliary equations (A). These equations are diagramed as circles. Straight lines indicate constants assigned in C-type equations or computed as initial values in N-type equations. Each equation has a number and a type (appendix A).

Each variable has a name and an abbreviation used in the DYNAMO notations (appendix B). After the decimal following each variable is a subscript that identifies the time of the variable's value. For each iteration, three successive junctions of computation intervals (DT) are designated J (past), K (present), and L (next). Rates, constant over

ch computational interval, are subscripted JK for the past interval and for the next interval. Levels and auxiliaries are subscripted J and because they have values only for past and present times.

The model determines timber harvest by sensing the current distribution of habitats, comparing it with the desired distribution, and then mputing the rates of harvest. The computations begin with data from an ventory of the current distribution of habitats in the forest. The ventory provides the initial area of the habitats in the model (table 2, time 0). Successive areas of habitats are computed by integration.

5.2.1 The Old-Growth Feedback Loop

The amount of old-growth habitat removed (ROG) is determined by the amount of timber accumulated for removal (OSA) divided by the delay in time for practical removal of timber (DRT). There are inevitable delays in removals that may be caused by weather conditions, availability of labor and machinery, and many other factors. The value for DRT is an estimate of the average period for these delays.

```
RCG.KL=CSA.K/DRT                                        1, R
DRT=2                                                   1.1, C
     ROG    - REMOVE OLD GROWTH (AREA/YEAR)
     OSA    - OLD GROWTH SALES ACCUMULATION (AREA)
     DRT    - DELAY FOR REMOVAL OF TIMBER (YEARS)
```

The accumulation of old-growth sales (OSA) models a bookkeeping process. The accounting is the integration of old-growth sales (OGS) and the removal of old growth (ROG).

```
OSA.K=OSA.J+DT*(OGS.JK-ROG.JK)                          2, L
CSA=OGS                                                 2.1, N
     OSA    - OLD GROWTH SALES ACCUMULATION (AREA)
     OGS    - OLD GROWTH SALES (AREA/YEAR)
     ROG    - REMOVE OLD GROWTH (AREA/YEAR)
```

Old-growth sales rate (OGS) is a product of the indicated old-growth sales (IOGS) and the flow rate of old-growth succession when the distribution of habitats is at the desired steady state (FOG). This flow rate, FOG, represents the acres of old growth ready for harvest each year when the forest is at equilibrium. It is derived by multiplying the total area of the forest (TAH) times the old-growth fraction (OGS), then dividing by the age for harvest of old growth. The age for harvest of old growth is computed by adding the age at which timber becomes old-growth habitat (AOG) to the specified delay for harvest of old-growth habitats (DOG). The total area of habitats (TAH) is the sum of the initial inventories. The transition ages (AMT and AOG) are computed from constants for the rates of succession. The constants used in this illustration for the Southern Appalachians are taken from Schnur (1937). For the old-growth habitats the ages are from unpublished data of Frothingham (see footnote 1) and the author.

The values for OGF, DOG, and DMT are control constants that define the mode of management being analyzed (table 1).

```
OGS.KL=IOGS.K*FOG                                          3, R
FCG=(TAH*OGF)/(DOG+AOG)                                    3.1, N
TAH=ISE+ISA+IP6+IP8+IP1+IMT+IOG                            3.2, N
AMT=DSE+DSA+DP6+DP8+DP1                                    3.3, N
ACG=AMT+DMT                                                3.4, N
```

OGS - OLD GROWTH SALES (AREA/YEAR)
IOGS - INDICATED OLD GROWTH SALES (DIMENSIONLESS)
FOG - FLOW OLD GROWTH HABITATS (AREA/YEAR)
TAH - TOTAL AREA ALL HABITATS (AREA)
OGF - FRACTION REMOVED THROUGH OLD GROWTH HABITAT (PERCENT)
DOG - DELAY FOR OLD GROWTH SUCCESSION (YEARS)
AOG - TRANSITION AGE OLD GROWTH (YEARS)
ISE - INVENTORY SEEDLINGS (AREA)
ISA - INVENTORY SAPLINGS (AREA)
IP6 - INVENTORY POLE-6 (AREA)
IP8 - INVENTORY POLE-8 (AREA)
IP1 - INVENTORY POLE-10 (AREA)
IMT - INVENTORY MATURE TIMBER (AREA)
IOG - INVENTORY OLD GROWTH (AREA)
AMT - TRANSITION AGE MATURE (YEARS)
DSE - DELAY FOR SEEDLING SUCCESSION (YEARS)
DSA - DELAY FOR SAPLING SUCCESSION (YEARS)
DP6 - DELAY FOR POLE-6 SUCCESSION (YEARS)
DP8 - DELAY FOR POLE-8 SUCCESSION (YEARS)
DP1 - DELAY FOR POLE-10 SUCCESSION (YEARS)
DMT - DELAY FOR MATURE HABITAT SUCCESSION (YEARS)

The sales of old-growth habitat are limited by a table function (IOGS) based on the coverage of old-growth habitat (COG) (fig. 10). When the coverage of old-growth habitat is less than half of the amount desired at equilibrium, no harvest of old growth is permitted. When the coverage of old-growth habitat is equal to the amount desired, the rate of harvest is limited to the flow of old-growth succession (FOG). When there is more area in old-growth habitat than the goal, the rate of harvest is increased, but never to more than 1.3 times the flow of old-growth succession.

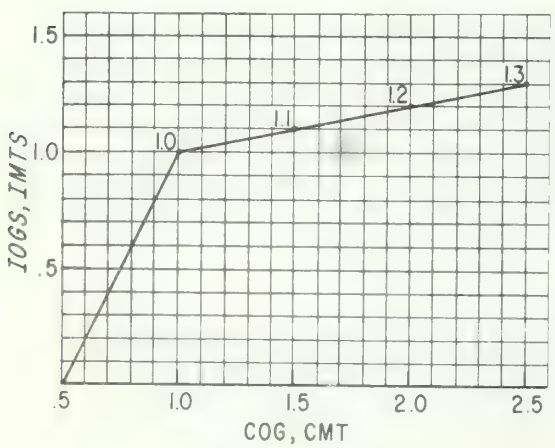


Figure 10.--The indicated diversion of old-growth and mature timber habitats versus the coverage of old-growth and mature timber habitats. (See equations 4 and 9.)

```
IOGS.K=TABHL(TIDM,COG.K,.5,2.5,.5)                    4, A
TIDM=0/1/1.1/1.2/1.3                                  4.1, T
     IOGS   - INDICATED OLD GROWTH SALES (DIMENSIONLESS)
     TIDM   - TABLE INDICATED DIVERSION TIMBER
                (DIMENSIONLESS)
     COG    - COVERAGE OF OLD GROWTH HABITAT
                (DIMENSIONLESS)
```

The coverage of old-growth habitat (COG) is the amount of old-growth habitat reserves (the unsold area actually covered by old timber, OGR) divided by the equilibrium old-growth habitat (EOG). The equilibrium goal for old-growth habitats (EOG) is the product of flow rate of succession into old-growth habitats (FOG) and the delay of old growth (DOG).

```
COG.K=CGR.K/EOG                                       5, A
EOG=FOG*DOG                                           5.1, N
     COG    - COVERAGE OF OLD GROWTH HABITAT
                (DIMENSIONLESS)
     OGR    - OLD GROWTH RESERVES (AREA)
     EOG    - EQUILIBRIUM OLD GROWTH HABITAT (AREA)
     FOG    - FLOW OLD GROWTH HABITATS (AREA/YEAR)
     DOG    - DELAY FOR OLD GROWTH SUCCESSION (YEARS)
```

5.2.2 The Mature Timber Feedback Loop

The amount of mature timber removed (RMT) is determined by the decision to harvest and the delay for removal. The amount of timber accumulated for removal (MHA) divided by the delay in removal of timber (DRT) estimates the amount removed for each interval of time.

```
RMT.KL=MHA.K/DRT                                      6, R
     RMT    - REMOVE MATURE HABITAT (AREA/YEAR)
     MHA    - MATURE HABITAT SALES ACCUMULATION (AREA)
     DRT    - DELAY FOR REMOVAL OF TIMBER (YEARS)
```

The accumulation of mature timber sales (MHA) models a bookkeeping process. This accounting integrates mature timber sales (MTS) and removal of mature timber (RMT).

```
MHA.K=MHA.J+DT*(MTS.JK-RMT.JK)                        7, L
MHA=MTS                                               7.1, N
     MHA    - MATURE HABITAT SALES ACCUMULATION (AREA)
     MTS    - MATURE TIMBER SALES (AREA/YEAR)
     RMT    - REMOVE MATURE HABITAT (AREA/YEAR)
```

The rate of mature timber sales (MTS) is an important decision point in the model. To make this part of the model clear, the rate equations are separated into a number of auxiliary equations. The model seeks a goal, a distribution of habitats maintained at equilibrium by a steady flow of succession. The rate of mature timber sales (MTS) is balanced between the indicator of mature timber habitat

available for diversion (IMTS) and the indicator of habitat diversion (new seedling habitat) required for the goal (HDI). This balance regulates the distribution of seedling, sapling, pole, and mature timber habitats. The model selects the minimum rate of habitat diversion that will achieve the goal. The minimum indicator of diversion required, either HDI or IMTS, is multiplied by the flow rate of succession to mature timber habitats (FMT). This flow rate (FMT) is the product of the total area of habitats (TAH) and the designated mature timber fraction, divided by the desired age of harvest. This number represents the annual flow of acreage into the mature timber habitat when the model is at the steady state.

```
MTS.KL=(MIN(HDI.K,IMTS.K))*FMT                          8, R
FMT=(TAH*(1-OGF))/(AMT+DMT)                             8.1, N
```

MTS - MATURE TIMBER SALES (AREA/YEAR)
MIN - FUNCTION SELECTS MINIMUM VALUE
HDI - HABITAT DIVERSION INDICATED (DIMENSIONLESS)
IMTS - INDICATED MATURE TIMBER SALES (DIMENSIONLESS)
FMT - FLOW MATURE TIMBER HABITATS (AREA/YEAR)
TAH - TOTAL AREA ALL HABITATS (AREA)
OGF - FRACTION REMOVED THROUGH OLD GROWTH HABITAT (PERCENT)
AMT - TRANSITION AGE MATURE (YEARS)
DMT - DELAY FOR MATURE HABITAT SUCCESSION (YEARS)

The indicator for diversion of mature timber (IMTS) is calculated by a table function which is based on a comparison of desired mature timber habitat with actual coverage (CMT). The table (fig. 10) for the indicated diversion of mature timber habitat limits the harvest of mature timber to 0 when the coverage of mature timber is less than half of that desired. When the actual coverage equals the desired coverage, the indicated diversion of mature timber is 1. When there is more mature timber than desired at equilibrium, the rate of harvest is increased, but never to more than 1.3 times the flow rate of succession into mature timber habitats.

```
IMTS.K=TABHL(TIDM,CMT.K,.5,2.5,.5)                      9, A
```

IMTS - INDICATED MATURE TIMBER SALES (DIMENSIONLESS)
TIDM - TABLE INDICATED DIVERSION TIMBER (DIMENSIONLESS)
CMT - COVERAGE OF MATURE HABITAT (DIMENSIONLESS)

The coverage of mature timber habitat (CMT) is the ratio of current mature timber reserves (MTR) to the equilibrium goal for mature timber (EMT). The equilibrium goal (EMT) is a product of the flow rate of succession for all habitats (FDH) and the period of delay desired for mature timber habitats (DMT). The delay of mature timber habitats (DMT) is a constant specified as part of the mode of management. The flow rate of succession for all habitats (FDH) is the sum of the flow rate into mature timber (FMT) and the flow rate into old-growth habitats (FOG).

```
CMT.K=MTR.K/EMT                                          10, A
EMT=FDH*DMT                                              10.1, N
FDH=FMT+FOG                                              10.2, N
     CMT     - COVERAGE OF MATURE HABITAT  (DIMENSIONLESS)
     MTR     - MATURE TIMBER RESERVES (AREA)
     EMT     - EQUILIBRIUM MATURE HABITAT (AREA)
     FDH     - FLOW DIVERTED HABITATS (AREA/YEAR)
     DMT     - DELAY FOR MATURE HABITAT SUCCESSION (YEARS)
     FMT     - FLOW MATURE TIMBER HABITATS (AREA/YEAR)
     FOG     - FLOW OLD GROWTH HABITATS (AREA/YEAR)
```

The amount of harvest needed to maintain seedling habitats (HDI) is calculated by a table function (fig. 11) based on the coverage of seedling habitats (CDH), which is the area diverted from mature and old-growth timber. When the coverage of seedling habitat is 0, the rate of diversion increases up to 1.3 times the flow of area into mature timber habitats (FMT). When the coverage of seedling habitats is 1, the harvest is limited to the flow rate, FMT. When the coverage is more than 1, the harvest is reduced; it decreases to 0 when the coverage of seedling habitats is 3 or more.

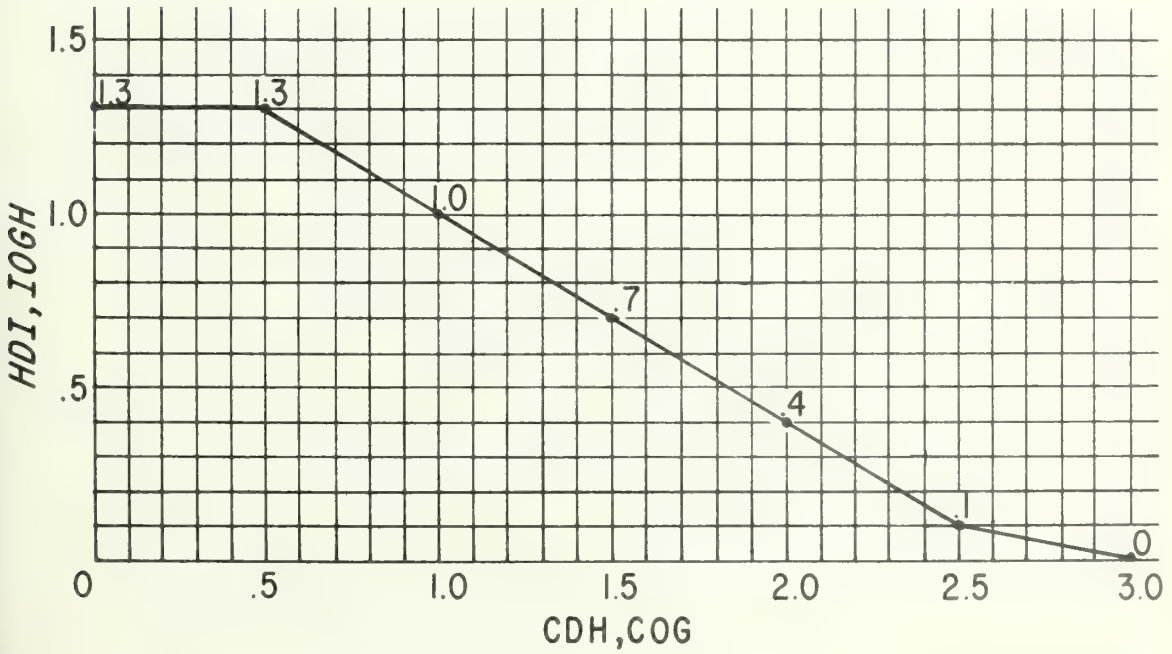


Figure 11.--The habitat diversion indicated versus the coverage of diverted habitats (equation 11,A) and the coverage of old growth (equation 14,A).

```
HDI.K=TABHL(THDI,CDH.K,0,3,.5)                          11, A
THDI=1.3/1.3/1/.7/.4/.1/0                               11.1, T
     HDI    - HABITAT DIVERSION INDICATED (DIMENSIONLESS)
     THDI   - TABLE HABITAT DIVERSION (DIMENSIONLESS)
     CDH    - COVERAGE OF DIVERTED HABITATS
                (DIMENSIONLESS)
```

The coverage of seedling habitats (CDH) is the ratio of the area currently in seedling habitats (SE) and the equilibrium goal (EDH). This equilibrium (EDH) is a product of the flow rate of succession for all habitats (FDH) and the period of delay for seedling habitats (DSE). The delay for seedling habitats is the succession period, determined by experience and research, for seedling habitats to grow to sapling habitats (sec. 3.3).

```
CDH.K=SE.K/EDH                                          12, A
EDH=FDH*DSE                                             12.1, N
     CDH    - COVERAGE OF DIVERTED HABITATS
                (DIMENSIONLESS)
     SE     - SEEDLING HABITAT (AREA)
     EDH    - EQUILIBRIUM DIVERTED HABITAT (AREA)
     FDH    - FLOW DIVERTED HABITATS (AREA/YEAR)
     DSE    - DELAY FOR SEEDLING SUCCESSION (YEARS)
```

5.2.3 The Transfer from Mature Timber to Old Growth

To determine the rate of transfer from mature timber to old-growth habitat, the model chooses the smaller of two indicators: that for diversion of mature timber (IMTS) and that for the amount of old growth required for the goal (IOGH). The smaller indicator multiplied by the rate of flow of succession for old-growth habitats (FOG).

```
TOG.KL=(MIN(IOGH.K,IMTS.K))*FOG                         13, R
     TOG    - TRANSFER TO OLD GROWTH (AREA/YEAR)
     MIN    - FUNCTION SELECTS MINIMUM VALUE
     IOGH   - INDICATED OLD GROWTH HABITAT
                (DIMENSIONLESS)
     IMTS   - INDICATED MATURE TIMBER SALES
                (DIMENSIONLESS)
     FOG    - FLOW OLD GROWTH HABITATS (AREA/YEAR)
```

The indicator for amount of old growth required (IOGH) is computed from a table function based on the coverage of old-growth habitat (COG) (fig. 11). At 0 coverage, IOGH is 1.3 times flow into old-growth habitats (FOG). When actual coverage equals desired coverage, the IOGH equals FOG. When the coverage of old-growth habitat is more than 1, the indicator is gradually reduced until it is 0 when the coverage is 3.

```
IOGH.K=TABHL(THDI,COG.K,0,3,.5)                          14, A
    IOGH   - INDICATED OLD GROWTH HABITAT
               (DIMENSIONLESS)
    THDI   - TABLE HABITAT DIVERSION (DIMENSIONLESS)
    COG    - COVERAGE OF OLD GROWTH HABITAT
               (DIMENSIONLESS)
```

5.2.4 The Flow of Succession

Once the old-growth and mature timber habitats are diverted, the seedling habitats transform through the stages of succession. This process is modeled by rate and level equations (fig. 9). Note that equations 22 and 23 were inadvertently numbered out of sequence.

```
SE.K=SE.J+DT*(RMT.JK+ROG.JK-SSH.JK)                      15, L
SE=ISE                                                   15.1, N
    SE     - SEEDLING HABITAT (AREA)
    RMT    - REMOVE MATURE HABITAT (AREA/YEAR)
    ROG    - REMOVE OLD GROWTH (AREA/YEAR)
    SSH    - SUCCESSION TO SAPLING HABITAT (AREA/YEAR)
    ISE    - INVENTORY SEEDLINGS (AREA)

SSH.KL=SE.K/DSE                                          16, R
    SSH    - SUCCESSION TO SAPLING HABITAT (AREA/YEAR)
    SE     - SEEDLING HABITAT (AREA)
    DSE    - DELAY FOR SEEDLING SUCCESSION (YEARS)

SA.K=SA.J+DT*(SSH.JK-SPH.JK)                             17, L
SA=ISA                                                   17.1, N
    SA     - SAPLING HABITAT (AREA)
    SSH    - SUCCESSION TO SAPLING HABITAT (AREA/YEAR)
    SPH    - SUCCESSION TO POLE HABITAT (AREA/YEAR)
    ISA    - INVENTORY SAPLINGS (AREA)

SPH.KL=SA.K/DSA                                          18, R
    SPH    - SUCCESSION TO POLE HABITAT (AREA/YEAR)
    SA     - SAPLING HABITAT (AREA)
    DSA    - DELAY FOR SAPLING SUCCESSION (YEARS)

P6.K=P6.J+DT*(SPH.JK-SP8.JK)                             19, L
P6=IP6                                                   19.1, N
    P6     - POLE 6-INCH HABITAT (AREA)
    SPH    - SUCCESSION TO POLE HABITAT (AREA/YEAR)
    SP8    - SUCCESSION TO POLE-8 (AREA/YEAR)
    IP6    - INVENTORY POLE-6 (AREA)

SP8.KL=P6.K/DP6                                          20, R
    SP8    - SUCCESSION TO POLE-8 (AREA/YEAR)
    P6     - POLE 6-INCH HABITAT (AREA)
    DP6    - DELAY FOR POLE-6 SUCCESSION (YEARS)
```

```
P8.K=P8.J+DT*(SP8.JK-SP1.JK)                                    21, L
P8=IP8                                                          21.1, N
     P8      - POLE 8-INCH HABITAT (AREA)
     SP8     - SUCCESSION TO POLE-8 (AREA/YEAR)
     SP1     - SUCCESSION TO POLE-10 (AREA/YEAR)
     IP8     - INVENTORY POLE-8 (AREA)

P1.K=P1.J+DT*(SP1.JK-SMT.JK)                                    22, L
     P1      - POLE 10-INCH HABITAT (AREA)
     SP1     - SUCCESSION TO POLE-10 (AREA/YEAR)
     SMT     - SUCCESSION TO MATURE TIMBER (AREA/YEAR)

SP1.KL=P8.K/DP8                                                 23, R
P1=IP1                                                          23.1, N
     SP1     - SUCCESSION TO POLE-10 (AREA/YEAR)
     P8      - POLE 8-INCH HABITAT (AREA)
     DP8     - DELAY FOR POLE-8 SUCCESSION (YEARS)
     P1      - POLE 10-INCH HABITAT (AREA)
     IP1     - INVENTORY POLE-10 (AREA)


SMT.KL=P1.K/DP1                                                 24, R
     SMT     - SUCCESSION TO MATURE TIMBER (AREA/YEAR)
     P1      - POLE 10-INCH HABITAT (AREA)
     DP1     - DELAY FOR POLE-10 SUCCESSION (YEARS)

MTR.K=MTR.J+DT*(SMT.JK-TOG.JK-MTS.JK)                           25, L
MTR=IMT                                                         25.1, N
     MTR     - MATURE TIMBER RESERVES (AREA)
     SMT     - SUCCESSION TO MATURE TIMBER (AREA/YEAR)
     TOG     - TRANSFER TO OLD GROWTH (AREA/YEAR)
     MTS     - MATURE TIMBER SALES (AREA/YEAR)
     IMT     - INVENTORY MATURE TIMBER (AREA)

OGR.K=OGR.J+DT*(TOG.JK-OGS.JK)                                  26, L
OGR=IOG                                                         26.1, N
     OGR     - OLD GROWTH RESERVES (AREA)
     TOG     - TRANSFER TO OLD GROWTH (AREA/YEAR)
     OGS     - OLD GROWTH SALES (AREA/YEAR)
     IOG     - INVENTORY OLD GROWTH (AREA)
```

5.3 Supplementary Information

Supplementary equations are used to derive information about the dynamics of the model, including the proportion of area which is covered by each type of habitat at any point in time. This information is needed to project benefits. Other supplementary equations can be added as the need arises.

```
PSE.K=SE.K/TAH                                                  27, S
    PSE     - PROPORTION OF AREA IN SEEDLING HABITAT
              (PERCENT)
    SE      - SEEDLING HABITAT (AREA)
    TAH     - TOTAL AREA ALL HABITATS (AREA)

PSA.K=SA.K/TAH                                                  28, S
    PSA     - PROPORTION OF AREA IN SAPLING HABITAT
              (PERCENT)
    SA      - SAPLING HABITAT (AREA)
    TAH     - TOTAL AREA ALL HABITATS (AREA)

PP6.K=P6.K/TAH                                                  29, S
    PP6     - PROPORTION OF AREA IN POLE-6 HABITAT
              (PERCENT)
    P6      - POLE 6-INCH HABITAT (AREA)
    TAH     - TOTAL AREA ALL HABITATS (AREA)

PP8.K=P8.K/TAH                                                  30, S
    PP8     - PROPORTION OF AREA IN POLE-8 HABITAT
              (PERCENT)
    P8      - POLE 8-INCH HABITAT (AREA)
    TAH     - TOTAL AREA ALL HABITATS (AREA)

PP1.K=P1.K/TAH                                                  31, S
    PP1     - PROPORTION OF AREA IN POLE-10 HABITAT
              (PERCENT)
    P1      - POLE 10-INCH HABITAT (AREA)
    TAH     - TOTAL AREA ALL HABITATS (AREA)

PMT.K=MT.K/TAH                                                  32, S
    PMT     - PROPORTION OF AREA IN MATURE TIMBER HABITAT
              (PERCENT)
    MT      - MATURE TIMBER HABITAT (AREA)
    TAH     - TOTAL AREA ALL HABITATS (AREA)

MT.K=MTR.K+MHA.K                                                33, S
    MT      - MATURE TIMBER HABITAT (AREA)
    MTR     - MATURE TIMBER RESERVES (AREA)
    MHA     - MATURE HABITAT SALES ACCUMULATION (AREA)

POG.K=OG.K/TAH                                                  34, S
    POG     - PROPORTION OF AREA IN OLD GROWTH HABITAT
              (PERCENT)
    OG      - OLD GROWTH HABITAT (AREA)
    TAH     - TOTAL AREA ALL HABITATS (AREA)

OG.K=OGR.K+OSA.K                                                35, S
    OG      - OLD GROWTH HABITAT (AREA)
    OGR     - OLD GROWTH RESERVES (AREA)
    OSA     - OLD GROWTH SALES ACCUMULATION (AREA)

PSEA.K=(SE.K+SA.K)/TAH                                          36, S
    PSEA    - PROPORTION OF AREA IN SEEDLINGS AND
              SAPLINGS (PERCENT)
    SE      - SEEDLING HABITAT (AREA)
    SA      - SAPLING HABITAT (AREA)
    TAH     - TOTAL AREA ALL HABITATS (AREA)
```

```
P08M.K=(P8.K+P1.K+MT.K)/TAH                                    37, S
    P08M   - PROPORTION OF AREA IN POLE-8,POLE-10 AND
               MATURE HABITATS(PERCENT)
    P8     - POLE 8-INCH HABITAT (AREA)
    P1     - POLE 10-INCH HABITAT (AREA)
    MT     - MATURE TIMBER HABITAT (AREA)
    TAH    - TOTAL AREA ALL HABITATS (AREA)

P1M.K=(P1.K+MT.K)/TAH                                          38, S
    P1M    - PROPORTION OF AREA IN POLE-10 AND MATURE
               HABITATS (PERCENT)
    P1     - POLE 10-INCH HABITAT (AREA)
    MT     - MATURE TIMBER HABITAT (AREA)
    TAH    - TOTAL AREA ALL HABITATS (AREA)

PMC.K=(MT.K+OG.K)/TAH                                          39, S
    PMO    - PROPORTION OF AREA IN MATURE AND OLD GROWTH
               HABITATS (PERCENT)
    MT     - MATURE TIMBER HABITAT (AREA)
    OG     - OLD GROWTH HABITAT (AREA)
    TAH    - TOTAL AREA ALL HABITATS (AREA)

PSMT.K=RMT.JK/(RMT.JK+ROG.JK+E)                                40, S
E=.01                                                          40.1, C
    PSMT   - PROPORTION OF SALES FROM MATURE TIMBER
               (PERCENT)
    RMT    - REMOVE MATURE HABITAT (AREA/YEAR)
    ROG    - REMOVE OLD GROWTH (AREA/YEAR)
    E      - EQUILIBRIUM CONSTANT (DIMENSION OF
               VARIABLE)

PSOG.K=ROG.JK/(RMT.JK+ROG.JK+E)                                41, S
    PSOG   - PROPORTION OF SALES FROM OLD GROWTH
               (PERCENT)
    ROG    - REMOVE OLD GROWTH (AREA/YEAR)
    RMT    - REMOVE MATURE HABITAT (AREA/YEAR)
    E      - EQUILIBRIUM CONSTANT (DIMENSION OF
               VARIABLE)
```

5.4 Regulation of the Size of Openings

The size and number of openings do not affect the amount of total area harvested for timber. The size of openings does affect the number of openings for a given rate of removal, and relatively small rates of removal may limit the size of openings. Also, harvesting in very small openings reduces the efficiency of timber production (sec. 6.1).

An average size of openings is chosen as part of the mode of management, according to the benefits desired. In practice, however, variations in topography, streams, accessibility, and other factors vary the desired size of openings. Consequently, the model includes a random variance in size of openings (NORMRN).

The size of openings may be limited by the harvest of very small amounts of timber. The model computes these opening sizes. For a given mode of management, we specify the size of opening desired (ISOM) and the associated standard deviation for harvesting mature timber (ISDM). The

model limits the size of openings to that possible with the annual rate of removal of mature timber (RMT). This is achieved in equation 43,S by selecting the minimum value of either ISOM or RMT. If RMT is less than ISOM, the standard deviation for the opening must also be corrected. In equation 44,S, the model selects either ISDM or 0.1 of the area harvested (RMT), whichever is smaller. Multiplying RMT by 0.1 is an arbitrary way to reduce the variance in size of openings when the opening size happens to be limited by the rate of harvest. The same kinds of computations are made for the size of openings for old-growth habitat.

```
SOMT.K=NORMRN(ASOM.K,SDMT.K)                                    42, S
    SOMT   - SIZE OF OPENINGS IN MATURE HABITAT (AREA)
    NORMRN - NORMAL DEVIATE RANDOM NUMBER FUNCTION
    ASOM   - AVERAGE SIZE OPENINGS MATURE HABITAT (AREA)
    SDMT   - STANDARD DEVIATION OPENINGS MATURE HABITAT
             (AREA)

ASOM.K=MIN(ISOM,RMT.JK)                                         43, S
    ASOM   - AVERAGE SIZE OPENINGS MATURE HABITAT (AREA)
    MIN    - FUNCTION SELECTS MINIMUM VALUE
    ISOM   - DESIRED AVERAGE SIZE OF OPENING MATURE
             HABITAT (AREA)
    RMT    - REMOVE MATURE HABITAT (AREA/YEAR)

SDMT.K=MIN(ISDM,(RMT.JK/10))                                    44, S
    SDMT   - STANDARD DEVIATION OPENINGS MATURE HABITAT
             (AREA)
    MIN    - FUNCTION SELECTS MINIMUM VALUE
    ISDM   - DESIRED STANDARD DEVIATION OPENINGS MATURE
             HABITAT (AREA)
    RMT    - REMOVE MATURE HABITAT (AREA/YEAR)

SOOG.K=NORMRN(ASOG.K,SDOG.K)                                    45, S
    SOOG   - SIZE OF OPENINGS IN OLD GROWTH (AREA)
    NORMRN - NORMAL DEVIATE RANDOM NUMBER FUNCTION
    ASOG   - AVERAGE SIZE OF OPENINGS OLD GROWTH (AREA)
    SDOG   - STANDARD DEVIATION OPENINGS OLD GROWTH
             (AREA)

ASOG.K=MIN(ISOG,ROG.JK)                                         46, S
    ASOG   - AVERAGE SIZE OF OPENINGS OLD GROWTH (AREA)
    MIN    - FUNCTION SELECTS MINIMUM VALUE
    ISOG   - DESIRED AVERAGE SIZE OF OPENING OLD GROWTH
             (AREA)
    ROG    - REMOVE OLD GROWTH (AREA/YEAR)

SDOG.K=MIN(ISDO,(ROG.JK/10))                                    47. S
    SDOG   - STANDARD DEVIATION OPENINGS OLD GROWTH
             (AREA)
    MIN    - FUNCTION SELECTS MINIMUM VALUE
    ISDO   - DESIRED STANDARD DEVIATION OPENINGS OLD
             GROWTH (AREA)
    ROG    - REMOVE OLD GROWTH (AREA/YEAR)
```

The number of openings per square mile (OPM), the total number of openings (NOP), and the distribution of opening sizes (OPS) are computed for use in benefit and impact equations.

```
CPM.K=NOP.K/(TAH/640)                                          48, S
    OPM     - NUMBER OF OPENINGS PER SQUARE MILE (NUMBER/
              SQUARE MILE)
    NOP     - NUMBER OF OPENINGS (NUMBER)
    TAH     - TOTAL AREA ALL HABITATS (AREA)


NOP.K=(RMT.JK/(SOMT.K+E))+(ROG.JK/(SOOG.K+E))                  49, S
    NOP     - NUMBER OF OPENINGS (NUMBER)
    RMT     - REMOVE MATURE HABITAT (AREA/YEAR)
    SOMT    - SIZE OF OPENINGS IN MATURE HABITAT (AREA)
    E       - EQUILIBRIUM CONSTANT (DIMENSION OF
              VARIABLE)
    ROG     - REMOVE OLD GROWTH (AREA/YEAR)
    SOOG    - SIZE OF OPENINGS IN OLD GROWTH (AREA)

OPS.K=(PSMT.K*SOMT.K)+(PSOG.K*SOOG.K)                          50, S
    OPS     - OPENING SIZE DISTRIBUTION (PROPORTIONAL
              AREA)
    PSMT    - PROPORTION OF SALES FROM MATURE TIMBER
              (PERCENT)
    SOMT    - SIZE OF OPENINGS IN MATURE HABITAT (AREA)
    PSOG    - PROPORTION OF SALES FROM OLD GROWTH
              (PERCENT)
    SOOG    - SIZE OF OPENINGS IN OLD GROWTH (AREA)
```

6. A TECHNICAL REPORT ON SAMPLE ALGORITHMS FOR EASTERN HARDWOOD FORESTS

The algorithms are statements of relationship between the distribution of habitats in the forest and the benefits available from the forest. They are written as supplementary equations by which the model projects an estimate of benefits. Constructing and validating algorithms is part of the continuing application of the DYNAST-MB system (sec. 3.4).

Seventeen algorithms for eastern hardwood forests have been constructed for the current version of DYNAST-MB. While they are ready for use, and indeed have been used to screen modes of management for a pilot application of the model, they are best regarded as tentatively formulated examples. New algorithms can be formulated for other benefits, and the extant ones will need to be adjusted by experience and research.

The following sections describe the 17 algorithms and give sources for information used to construct them. In some cases, the listed sources are only examples selected from an abundance of published research.

6.1 Potential Timber Index (PTI)

The potential timber index (PTI) is the ratio of the volume of timber harvested under a given mode of management to the volume that would be expected if timber production were favored over all other benefits.

```
PTI.K=(TVO.K+TVM.K)/TIM                                    51, S
    PTI     - POTENTIAL TIMBER INDEX (DIMENSIONLESS)
    TVO     - TIMBER VOLUME OLD GROWTH (VOLUME UNITS)
    TVM     - TIMBER VOLUME MATURE TIMBER (VOLUME UNITS)
    TIM     - TIMBER INDEX MAXIMUM (VOLUME UNITS)
```

The data for the index come from Schnur (1937), modified by information from Beck and Della-Bianca (1970), Dale (1972), and unpublished data from Frothingham (see footnote 1), and the Forest Survey.

The mean annual increment of cubic volume for stands of mixed Appalachian hardwoods peaks at about 50 years of age (Schnur 1937). Yellow-poplar stands, less than 13 percent of the forest (Boyce and McClure 1975), may peak a few years earlier (Beck and Della-Bianca 1970). The age of 50 is used as the reference age to develop a timber yield index (TYI). The index assumes that 100-percent stocking and an average site index of 70 (Knight, in press) will be typical. Under these conditions it computes expected yields for a mode of management and compares them with the yield at age 50. Of course, other ages for maximum production of timber could be used as the reference age.

At 50 years of age the timber yield index (TYI) is 1.00 (table 3). As age increases, both the yield and the timber yield index increase, but at a decreasing rate. We do not have enough information to predict increments accurately beyond 110 years. From Frothingham's (see footnote 1) reports of measurements of recently felled virgin stands in 1915, it appears that yield in cubic volume may exceed 10,000 cubic feet per acre for a few stands at about 300 years of age. Frothingham reported that

most stands held more than 6,000 cubic feet per acre. Extending the yield to 5,600 cubic feet per acre at 320 years is probably conservative. The timber yield for different age classes is entered as a table function (fig. 12).

Table 3.--The periodic annual increment, mean annual increment, yield, and timber yield index for selected ages of hardwood forests in the Appalachians[1/]

Age	Periodic annual increment	Mean annual increment	Yield[2/]	Timber yield index (volume units/acre)[3/]
Years	- - - - - Cubic feet per acre - - - - -			
20	48	53	1,090	0.41
50	51	53	2,680	1
80	42	49	3,950	1.47
110	34	45	4,960	1.85
140	8	37	5,200	1.94
170	4	31	5,320	1.98
200	2	27	5,380	2.01
230	2	24	5,440	2.03
260	2	21	5,500	2.05
290	2	19	5,560	2.07
320	1	17	5,600	2.09

1/ Based on table 34 for site index 70 (Schnur 1937) and extended to older ages from unpublished data (see footnote 1, page 16.)
2/ Volume inside bark for all trees 0.6 inch d.b.h. and larger.
3/ Yield (cubic feet per acre) divided by 2,680.

The timber-maximum rotation age (TMR) is the age selected for harvest if timber is preferred over all other benefits. For maximum production of cubic volume to a 4-inch top the age would be 50 years (Schnur 1937). In the example, 80 years is used because this is a typical rotation age for maximum production of saw logs to a 9-inch top in the Appalachians.

A timber index maximum (TIM) is computed by multiplying the timber yield index (TYI) by the total area of habitat (TAH) and dividing by the rotation age for maximum yield (TMR). This is an index of the amount of timber expected per year if timber production were favored over all other benefits.

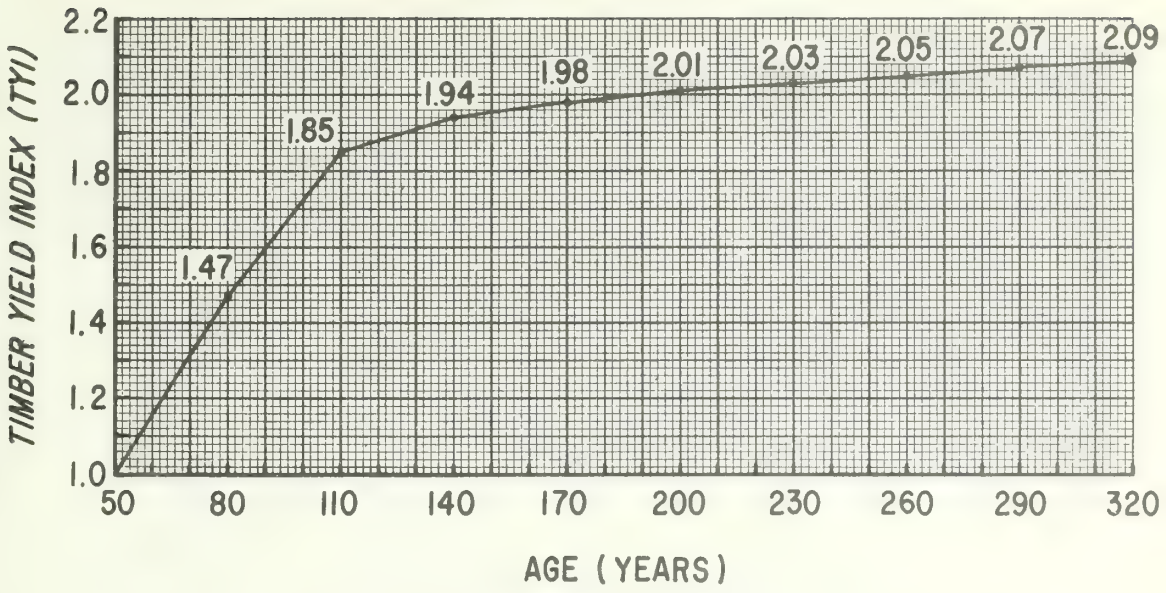


Figure 12.--Timber yield index (TYI) versus age of forest stands (years) / (equation 53). See table 3.

```
TVO.K=ROG.JK*OGVF.K*OFOG.K                                    52, S
    TVO     - TIMBER VOLUME OLD GROWTH (VOLUME UNITS)
    ROG     - REMOVE OLD GROWTH (AREA/YEAR)
    OGVF    - OLD GROWTH VOLUME FACTOR (VOLUME UNITS/
              AREA)
    OFOG    - OPENING FACTOR  OLD GROWTH (DIMENSIONLESS)

TVM.K=RMT.JK*MTVF.K*OFMT.K                                    53, S
TIM=(TAH/TMR)*TYI                                             53.1, N
TYI=TABHL(TTYI,TMR,20,320,30)                                 53.2, N
TTYI=.41/1/1.47/1.85/1.94/1.98/2.01/2.03/2.05/2.07/           53.3, T
  2.09
    TVM     - TIMBER VOLUME MATURE TIMBER (VOLUME UNITS)
    RMT     - REMOVE MATURE HABITAT (AREA/YEAR)
    MTVF    - MATURE TIMBER VOLUME FACTOR (VOLUME UNITS/
              AREA)
    OFMT    - OPENING FACTOR MATURE TIMBER
              (DIMENSIONLESS)
    TIM     - TIMBER INDEX MAXIMUM (VOLUME UNITS)
    TAH     - TOTAL AREA ALL HABITATS (AREA)
    TMR     - TIMBER MAXIMUM ROTATION AGE (YEARS)
    TYI     - TIMBER YIELD INDEX (VOLUME UNITS/UNIT AREA/
              YEAR)
    TTYI    - TABLE TIMBER YIELD INDEX (VOLUME UNITS/UNIT
              AREA/YEAR)
```

The timber yield has two components, mature timber volume (MTVF) and old-growth volume (OGVF). These are taken from the table for timber yield (fig. 12) according to age of harvest. The harvest ages for each of the fractions are dynamically corrected for volume per acre by estimating the ages of the stands at the time of harvest. The minimum age for mature timber is known from AMT, the average age for stands entering the mature timber stage. Each year an amount of area (FMT) enters the mature timber habitat. The age at harvest can be estimated by adding to the minimum age (AMT) the number of FMT's that have accumulated. Thus, the harvest age of mature timber (HAMT) is the amount of mature timber accumulated (MT) divided by the annual additions (FMT) and added to the minimum age (AMT). The harvest age for old growth (HAOG) is computed in a similar way.

```
MTVF.K=TABHL(TTYI,HAMT.K,20,320,30)                          54, S
    MTVF   - MATURE TIMBER VOLUME FACTOR (VOLUME UNITS/
             AREA)
    TTYI   - TABLE TIMBER YIELD INDEX (VOLUME UNITS/UNIT
             AREA/YEAR)
    HAMT   - HARVEST AGE MATURE TIMBER (YEARS)

HAMT.K=(MT.K/FMT)+AMT                                        55, S
    HAMT   - HARVEST AGE MATURE TIMBER (YEARS)
    MT     - MATURE TIMBER HABITAT (AREA)
    FMT    - FLOW MATURE TIMBER HABITATS (AREA/YEAR)
    AMT    - TRANSITION AGE MATURE (YEARS)

OGVF.K=TABHL(TTYI,HAOG.K,20,320,30)                          56, S
    OGVF   - OLD GROWTH VOLUME FACTOR (VOLUME UNITS/
             AREA)
    TTYI   - TABLE TIMBER YIELD INDEX (VOLUME UNITS/UNIT
             AREA/YEAR)
    HAOG   - HARVEST AGE OLD GROWTH (YEARS)

HAOG.K=(OG.K/FOG)+AOG                                        57, S
    HAOG   - HARVEST AGE OLD GROWTH (YEARS)
    OG     - OLD GROWTH HABITAT (AREA)
    FOG    - FLOW OLD GROWTH HABITATS (AREA/YEAR)
    AOG    - TRANSITION AGE OLD GROWTH (YEARS)
```

Because small openings reduce the growth rate for young trees and increase damage to surrounding trees during harvesting, the potential timber index (PTI) is reduced whenever the average diameter of openings is less than 3 acres. Harvest of timber from small openings injures the crowns, roots, and trunks of surrounding trees. The losses may not be apparent at the time of harvest, but in time the total yield is reduced (Nyland and others 1976; Biltonen and others 1976).

It is difficult to remove a large tree without creating an opening of at least 0.2 to 0.6 of an acre. The natural felling of trees in old-growth stands forms openings of this size (Williamson 1975). About 0.2 of an acre is the smallest size of opening for the felling, bucking, and removal of a large tree.

Growth in small openings is slow for seedlings, sprouts, and residual trees (Roach and Gingrich 1968; Trimble 1973; Marks 1974). Growth is also retarded near the border of an opening of any size. As the size of the clearing decreases, the ratio of internal area to

perimeter decreases. In a 3-acre, circular opening there are 100 square feet of area for each running foot of perimeter. In a half-acre opening, the area per perimeter foot is only 40 (fig. 13). The limitation on growing space caused by this border effect is probably insignificant for openings larger than 3 acres, but it rapidly becomes more severe for smaller openings. In the timber algorithm, the small opening factor (SOF) adjusts for losses on a curve which approximates the relative increase in perimeter when area declines (fig. 14).

```
OFMT.K=TABHL(TOFM,SOMT.K,0,3,.5)                          58, S
TOFM=.5/.8/.9/.93/.95/.98/1                               58.1, T
     OFMT   - OPENING FACTOR MATURE TIMBER
              (DIMENSIONLESS)
     TOFM   - TABLE OPENING FACTOR MULTIPLIER
              (DIMENSIONLESS)
     SOMT   - SIZE OF OPENINGS IN MATURE HABITAT (AREA)

OFOG.K=TABHL(TOFM,SOOG.K,0,3,.5)                          59, S
     OFOG   - OPENING FACTOR  OLD GROWTH (DIMENSIONLESS)
     TOFM   - TABLE OPENING FACTOR MULTIPLIER
              (DIMENSIONLESS)
     SOOG   - SIZE OF OPENINGS IN OLD GROWTH (AREA)
```

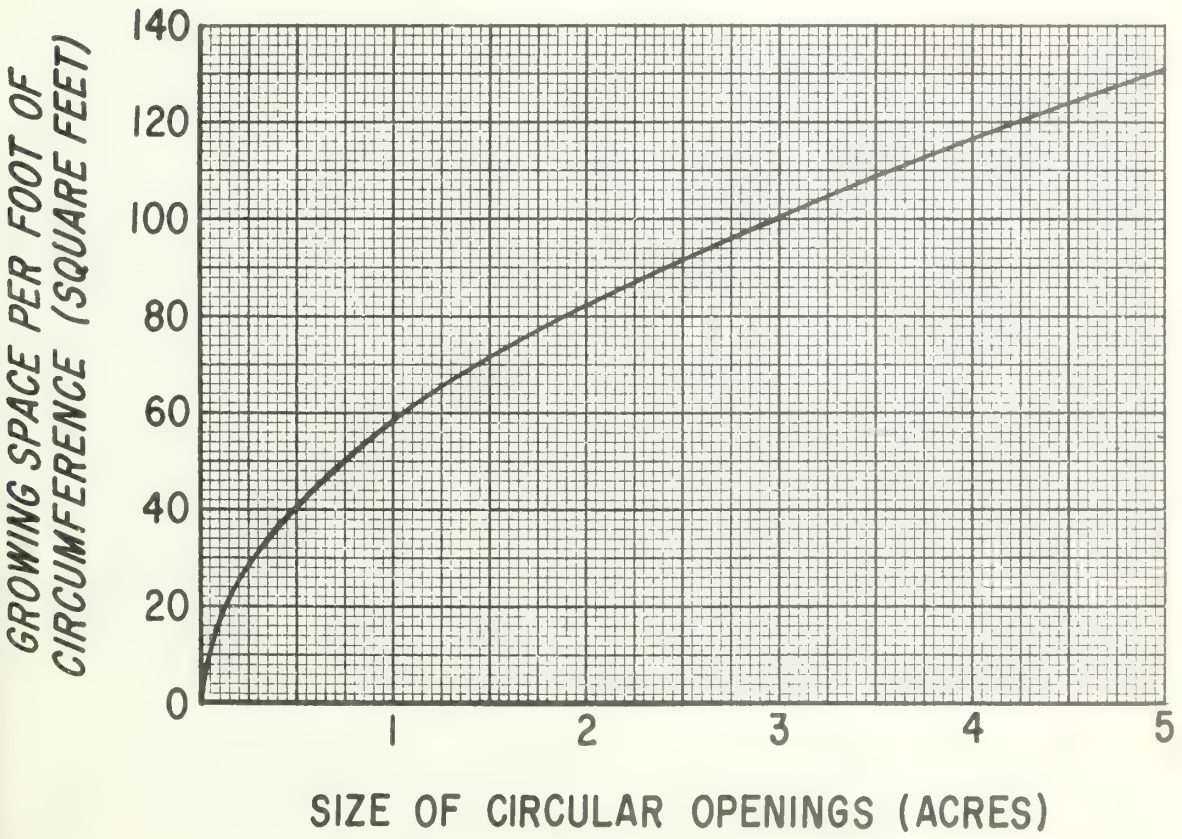


Figure 13.--The "border effect" in relation to the size of circular openings as indicated by the growing space per foot of circumference.

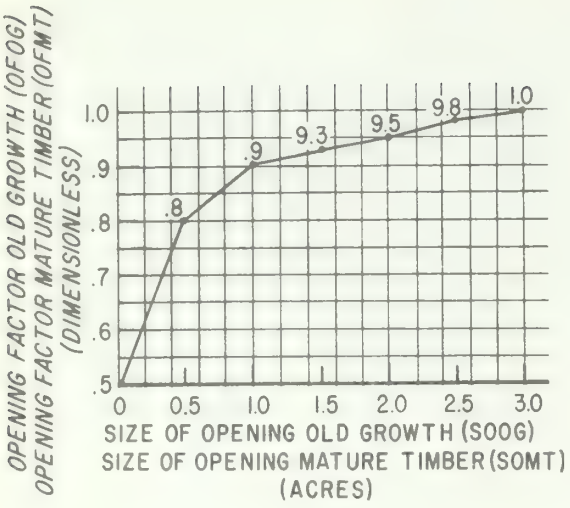


Figure 14.--Opening factors versus size of openings (table TOFM, equation 58).

6.2 Volume of Timber Harvested (VT)

The timber yield index used here (TYI, fig. 10) is a compromise. In the real forest, different site classes and densities of stocking affect the relationship between age and volume (Schnur 1937, table 34). Recently Carmean (1971) and others have presented evidence for improving predictions of growth by using polymorphic curves for separate species by site classes. In the DYNAST system, this amount of detail is not considered important for management decisions, since the primary concern is to consider the dynamics of the forest and to compare the relative yields of the modes of management, rather than to make specific predictions as one would in preparing for a sale. An enormous variety is generated by the mixture of different site index classes and species in an area; moreover, we cannot predict the site index of specific areas to be harvested in the future. Thus, it is necessary to use averaged values. Actually, the variance of site index from the average is relatively small for eastern hardwood forests (Schnur 1937; Knight, in press). For a specific management unit, the model can be started with the yield values listed in table 3. After several decades of inventories and timber sales, the figures in table 3 can be adjusted to predict yields more accurately.

This timber yield index (TYI) or one modified for a specific area can be used to approximate the volume of timber expected to be harvested with different modes of management. This is done separately for mature timber removals and for old-growth removals. Remembering that TVM (equation 53,S) is the number of volume units of mature timber harvested at a given time, we have only to multiply the number of TVM units by the volume of a unit to estimate the volume of mature timber removed (VMT, equation 104,S). The size of one volume unit at age 50 is found in the yield table (table 3) to be 2,680 cubic feet/acre, inside bark, for all

trees 0.6 inch d.b.h. and larger, stump to tip. The model runs presented in this report use a definition for merchantable volume units. In this definition (Y50, equation 104.1,C) the value of a volume unit is reduced to 2,520 cubic feet/acre as an estimate of volume inside bark, stump to a 4-inch top, for trees 4 inches and larger d.b.h. Since the timber yield relationship is one of a family of harmonized curves, other values can be used for the constant Y50.

The total volume of timber harvested (VT) is the sum of the volume of old growth harvested (VOG) and the volume of mature timber harvested (VMT).

6.3 Sediment Flow Index (SEMT)

The sediment index is described fully in section 2.2.3.

```
SEMT.K=TABHL(TSEMT,OPM.K,0,1,.2)                          60, S
TSEMT=0/.3/.6/.8/.9/1                                     60.1, T
    SEMT   - SEDIMENT INDEX (DIMENSIONLESS)
    TSEMT  - TABLE SEDIMENT INDEX
    OPM    - NUMBER OF OPENINGS PER SQUARE MILE (NUMBER/
             SQUARE MILE)
```

6.4 Ugliness Index (UGL)

The ugliness index reflects the disorderly appearance of recently harvested areas. The components of the index are the proportion of total area in seedling habitat (PSE), the number of openings per square mile (OPM), and the opening size distribution (OPS).

```
UGL.K=UGS.K*UGN.K*UGO.K                                   61, S
    UGL    - UGLINESS INDEX (DIMENSIONLESS)
    UGS    - UGLY DUE TO SEEDLINGS (DIMENSIONLESS)
    UGN    - UGLY DUE TO NUMBER OF OPENINGS
             (DIMENSIONLESS)
    UGO    - UGLINESS DUE TO OPENING SIZE DISTRIBUTION
             (DIMENSIONLESS)

UGS.K=TABHL(TUGS,PSE.K,0,.06,.01)                         62, S
TUGS=0/.1/.2/.3/.5/.7/1                                   62.1, T
    UGS    - UGLY DUE TO SEEDLINGS (DIMENSIONLESS)
    TUGS   - TABLE UGLY FOR SEEDLINGS
    PSE    - PROPORTION OF AREA IN SEEDLING HABITAT
             (PERCENT)

UGN.K=TABHL(TUGN,OPM.K,0,.8,.2)                           63, S
TUGN=1/.9/.7/.4/.01                                       63.1, T
    UGN    - UGLY DUE TO NUMBER OF OPENINGS
             (DIMENSIONLESS)
    TUGN   - TABLE UGLY FOR NUMBER OF OPENINGS
    OPM    - NUMBER OF OPENINGS PER SQUARE MILE (NUMBER/
             SQUARE MILE)
```

```
UGO.K=TABHL(TUGO,OPS.K,0,30,3)                          64, S
TUGO=0/.50/.65/.70/.75/.80/.85/.90/.95/.97/1            64.1, T
    UGO     - UGLINESS DUE TO OPENING SIZE DISTRIBUTION
              (DIMENSIONLESS)
    TUGO    - TABLE UGLINESS DUE TO OPENING SIZE
    OPS     - OPENING SIZE DISTRIBUTION (PROPORTIONAL
              AREA)
```

The index increases as any of these increases. For seedling habitat, the unacceptable limit for ugliness is 6 percent of the total area (fig. 15). For the number of openings, the limit is one per square mile per year (fig. 16). For size of openings, the limit is 30 acres (fig. 17).

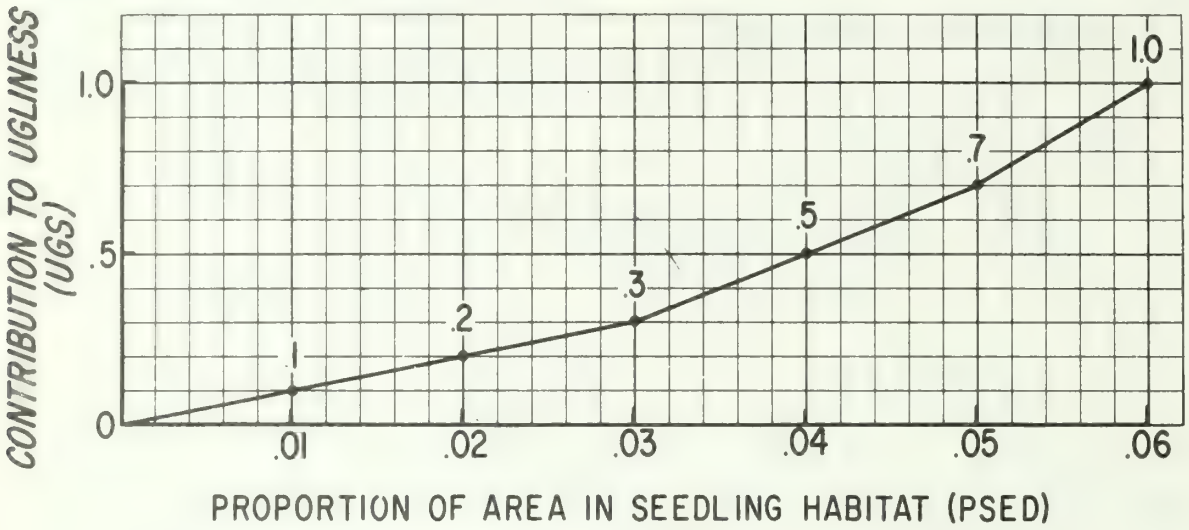


Figure 15.--Contribution to ugliness by the proportion of total area in seedling habitat.

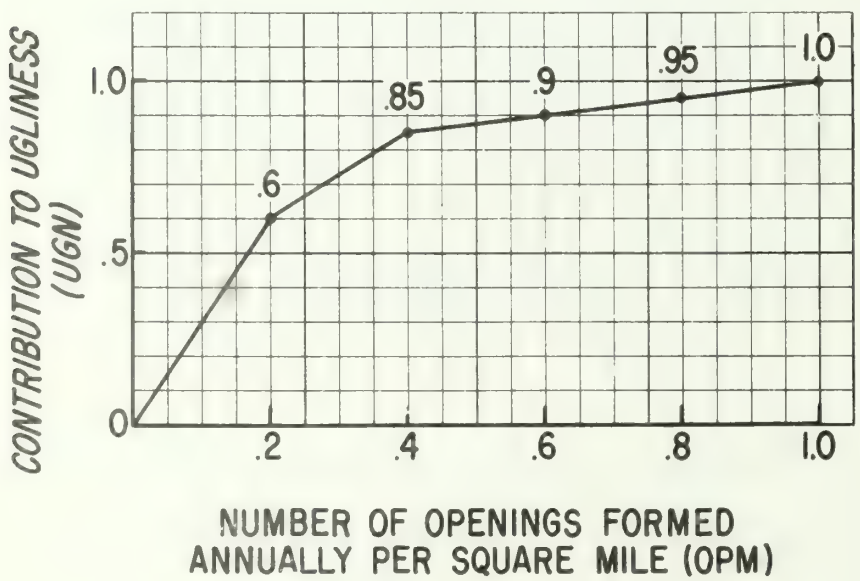


Figure 16.--Contribution to ugliness by the number of openings formed annually.

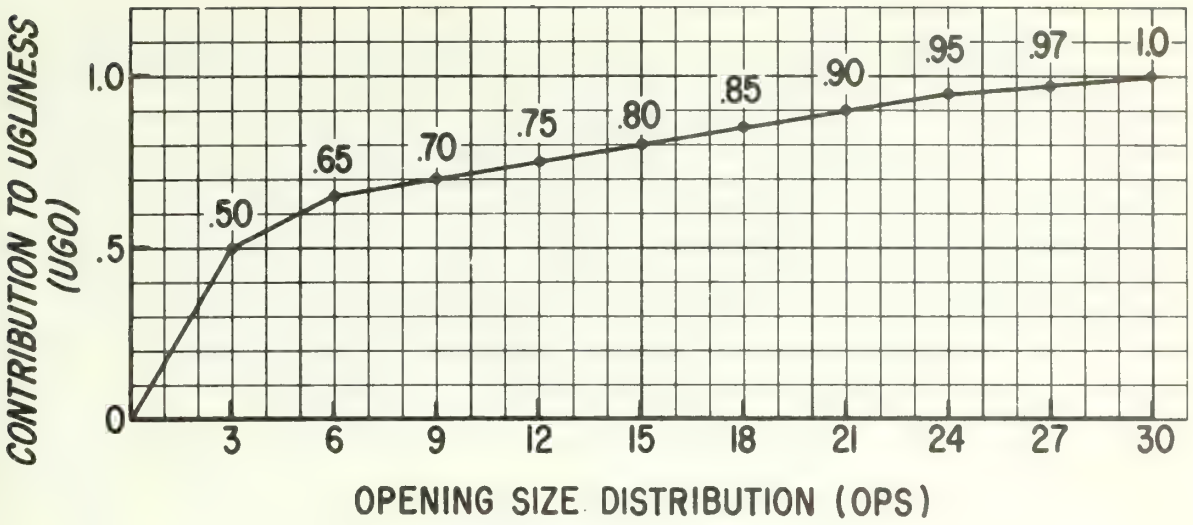


Figure 17.--Contribution to ugliness by the distribution of size and openings (OPS) (acres).

6.5 Visual Variety Index (VIS)

This index measures visual contrast in forest landscapes, on the assumption that variety contributes to esthetic appeal (see sec. 2.2). Among elements that can be controlled, the contrast in height of timber stands is the main variable. Three height classes are used to compute the index: old growth, other stands over 50 feet, and stands under 50 feet. The index rises to 1 when the three classes are in balance, with each occupying 30 to 40 percent of the area.

A 30-percent proportion of old growth is optimal for the visual appeal index (fig. 18). Beyond that, there is less room available for contrasting younger stands, and the index declines. The contribution to the index by the other two classes is highest when they are in exact balance (fig. 19).

The proportion of area in seedlings is important because the diversion of mature stands to seedling habitat regulates visual contrast in the older stands. Seedling stands also add contrast. However, the proportion of the total area in seedling habitat will rarely exceed 7 percent, and not more than 4 percent is needed to maintain a balanced distribution of older stands. The visual index can be 1 when seedling habitat equals 4 percent of the total area (fig. 20). As the proportion of seedling habitat increases or declines, an imbalance in contrast will begin to appear in the older stands as time progresses.

```
VIS.K=VSE.K*VBAL.K*VPOG.K                                    65, S
     VIS    - VISUAL APPEAL INDEX (DIMENSIONLESS)
     VSE    - VISUAL DUE TO SEEDLING HABITAT
                (DIMENSIONLESS)
     VBAL   - VISUAL APPEAL DUE TO BALANCED CONTRAST
                (DIMENSIONLESS)
     VPOG   - VISUAL DUE TO OLD GROWTH HABITATS
                (DIMENSIONLESS)
```

```
VSE.K=TABHL(TVSE,PSE.K,.01,.07,.01)                    66, S
TVSE=.2/.6/.9/1/.9/.6/.2                               66.1, T
     VSE     - VISUAL DUE TO SEEDLING HABITAT
                 (DIMENSIONLESS)
     TVSE    - TABLE VISUAL DUE TO SEEDLINGS
     PSE     - PROPORTION OF AREA IN SEEDLING HABITAT
                 (PERCENT)

VBAL.K=TABHL(TVBA,BAL.K,0,2,.5)                        67, S
TVBA=.4/.7/1/.7/.4                                     67.1, T
     VBAL    - VISUAL APPEAL DUE TO BALANCED CONTRAST
                 (DIMENSIONLESS)
     TVBA    - TABLE VISUAL FOR BALANCE
     BAL     - BALANCE OF TALL AND SHORT HABITATS
                 (DIMENSIONLESS)

BAL.K=(P8.K+P1.K+MT.K)/(SE.K+SA.K+P6.K)                68, S
     BAL     - BALANCE OF TALL AND SHORT HABITATS
                 (DIMENSIONLESS)
     P8      - POLE 8-INCH HABITAT (AREA)
     P1      - POLE 10-INCH HABITAT (AREA)
     MT      - MATURE TIMBER HABITAT (AREA)
     SE      - SEEDLING HABITAT (AREA)
     SA      - SAPLING HABITAT (AREA)
     P6      - POLE 6-INCH HABITAT (AREA)

VPOG.K=TABHL(TVPO,POG.K,0,.7,.1)                       69, S
TVPO=.4/.7/.9/1/.9/.8/.6/.4                            69.1, T
     VPOG    - VISUAL DUE TO OLD GROWTH HABITATS
                 (DIMENSIONLESS)
     TVPO    - TABLE VISUAL OLD GROWTH
     POG     - PROPORTION OF AREA IN OLD GROWTH HABITAT
                 (PERCENT)
```

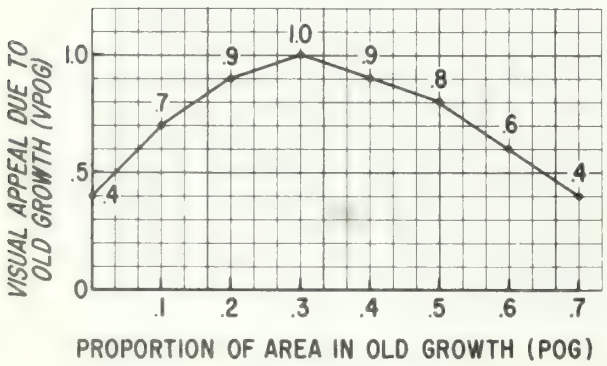


Figure 18.--Visual appeal due to the proportion of total area in old-growth habitat.

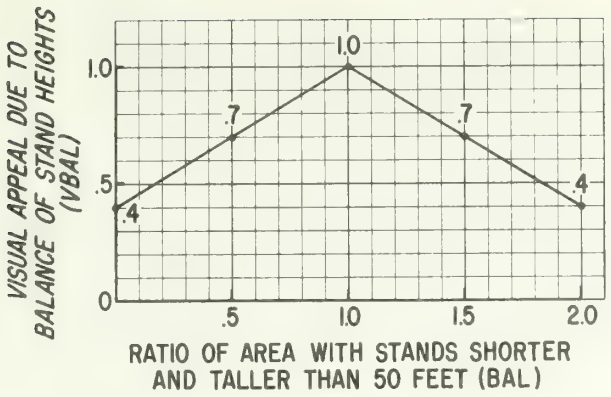
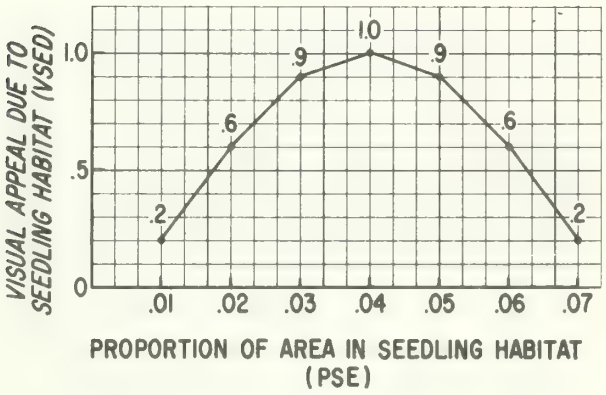


Figure 19.--Visual appeal due to the balance of stands shorter and taller than 50 feet.

Figure 20.--Visual appeal due to the proportion of area in seedling habitat.



6.6 Deer Habitat Index (DEER)

The adaptable whitetail eats many foods, including forage, acorns, nuts, fleshy fruits, and fungi. Hard mast, needed for winter food, and browse are the most important parts of the diet. Thus, mast-producing stands and seedling habitats contribute to the deer index.

Seedling habitat contributes an increasing amount of forage and soft mast as the proportion of area (PSE) increases to 7 percent. Larger proportions are assumed to make little or no additional contribution to the availability of forage (fig. 21).

Deer can use the forage most effectively when it is dispersed in a number of small openings. Figure 22 shows how the contribution to the deer index rises as openings decrease to 6 acres. The contribution of

opening type for deer (OTD) multiplied by the deer habitat index (HTD) reflects the way that the pattern of openings affects the availability of browse.

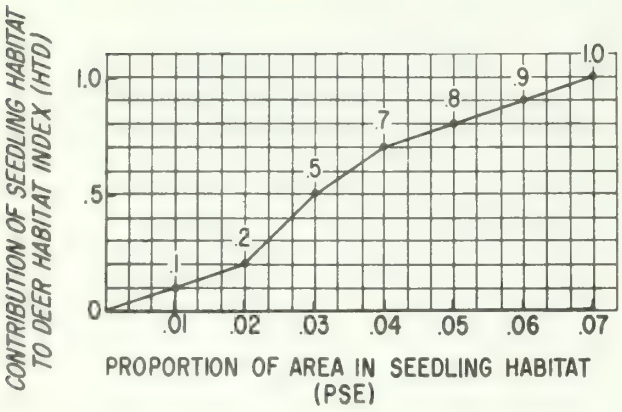


Figure 21.--Contribution of the proportion of area in seedling habitat to the deer habitat index.

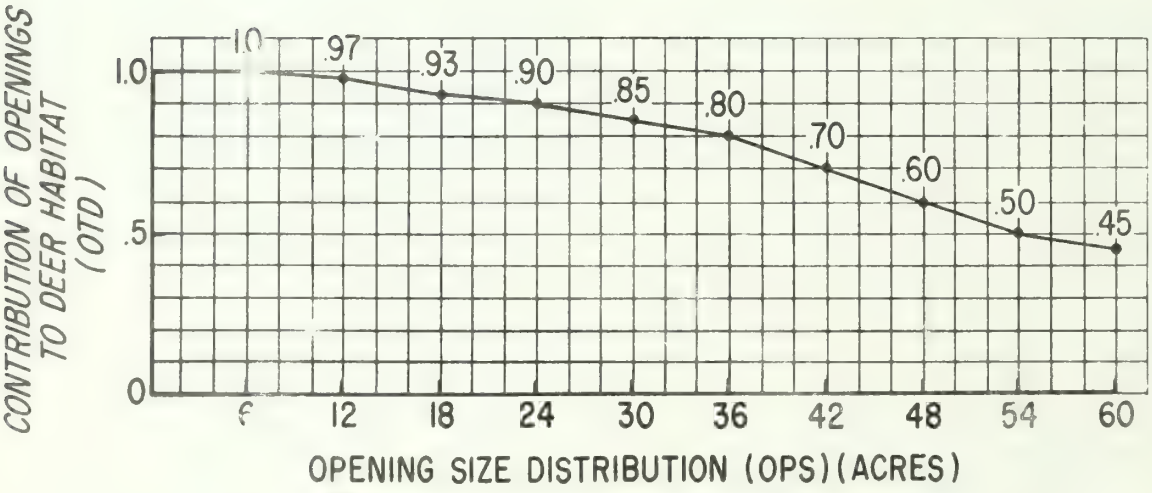


Figure 22.--The contribution of opening size distribution (OPS) to deer habitat.

The amount of hard mast is related to the proportion of area in 10-inch pole and mature timber habitat (fig. 23). Mast production is assumed to be adequate when 20 percent or more of the area is in mast-producing habitats. Species composition cannot easily be predicted (sec. 4.3) (McGee 1967, 1975; Trimble 1970, 1973; Sander and Clark 1971; McGee and Clark 1975), however, it is assumed that mast-producing species will be present and that the proportion of area in mast-producing age classes is a serviceable index to mast production.

```
DEER.K=HTD.K*OTD.K*DMA.K                                    70, S
     DEER   - DEER HABITAT INDEX (DIMENSIONLESS)
     HTD    - HABITAT TYPE DEER (DIMENSIONLESS)
     OTD    - OPENING TYPE DEER (DIMENSIONLESS)
     DMA    - DEER MAST AVAILABILITY (DIMENSIONLESS)

HTD.K=TABHL(THTD,PSE.K,0,.07,.01)                           71, S
THTD=0/.1/.2/.5/.7/.8/.9/1                                  71.1, T
     HTD    - HABITAT TYPE DEER (DIMENSIONLESS)
     THTD   - TABLE HABITAT TYPE DEER
     PSE    - PROPORTION OF AREA IN SEEDLING HABITAT
              (PERCENT)

OTD.K=TABHL(TOTD,OPS.K,0,60,6)                              72, S
TOTD=1/1/.97/.93/.9/.85/.8/.7/.6/.5/.45                     72.1, T
     OTD    - OPENING TYPE DEER (DIMENSIONLESS)
     TOTD   - TABLE OPENING TYPE DEER
     OPS    - OPENING SIZE DISTRIBUTION (PROPORTIONAL
              AREA)

DMA.K=TABHL(TDMA,P1M.K,0,.2,.05)                            73, S
TDMA=.1/.2/.5/.8/1                                          73.1, T
     DMA    - DEER MAST AVAILABILITY (DIMENSIONLESS)
     TDMA   - TABLE DEER MAST AVAILABILITY
     P1M    - PROPORTION OF AREA IN POLE-10 AND MATURE
              HABITATS (PERCENT)
```

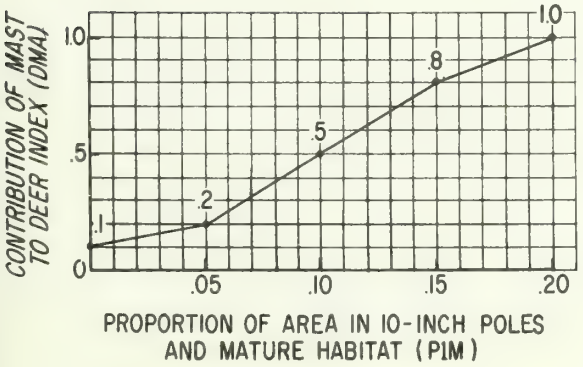


Figure 23.--Contribution of mast to deer habitat index versus the proportion of 10-inch poles and mature timber.

6.7 Squirrel Habitat Index (SQU)

Squirrels of all kinds are almost wholly dependent upon escape dens and forests that produce hard mast. Heavy production of hard mast requires large numbers of nut- and acorn-producing trees between 50 and 130 years of age and with diameters from 8 to 20 inches. The proportion of the areas in 8- and 10-inch pole timber and mature timber habitats is the most important component of the squirrel habitat index.

The second component of this index is the availability of dens for escape and nesting (USDA FS 1971). Dens are present in mature timber stands but are more frequent in the old-growth habitat. Although old growth typically has a lower production of mast than younger stands, some old growth, if well distributed, improves squirrel habitat.

The type-habitat index for squirrels (THS) increases as the proportion of area in 8-inch and 10-inch poles and mature timber (PO8M) increases (fig. 24). Only about 40 percent of an area can be maintained in these age classes for long periods, so this proportion is assumed to be the practical limit for the index.

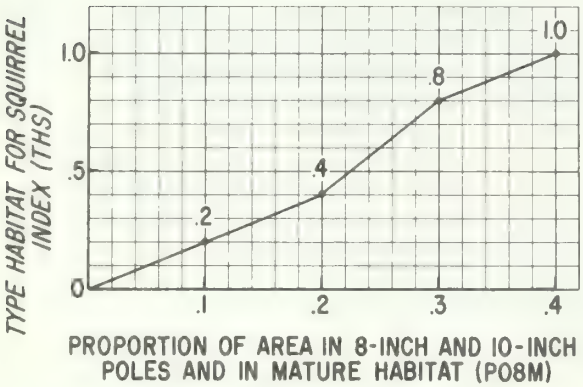


Figure 24.--Type of habitat for squirrel index versus the proportion of area in 8-inch and 10-inch poles and mature habitat.

A relatively small proportion of old-growth habitat, if well distributed through the management unit, can supply nest and den cavities. The index for dens (SDT) increases rapidly as the proportion of old growth increases from 0 to 30 percent of the total area (fig. 25). As the proportion of old-growth habitat increases, however, the proportion of stands in 8- to 10-inch pole timber and mature timber declines and the overall index declines. In this way the index reflects the relative distribution of stands for mast production and for cavities.

```
SQU.K=THS.K*SDT.K                                          74, S
    SQU    - SQUIRREL HABITAT INDEX (DIMENSIONLESS)
    THS    - TYPE HABITAT FOR SQUIRRELS (DIMENSIONLESS)
    SDT    - SQUIRREL DEN TREE INDEX (DIMENSIONLESS)

THS.K=TABHL(TTHS,PO8M.K,0,.4,.1)                           75, S
TTHS=0/.2/.4/.8/1                                          75.1, T
    THS    - TYPE HABITAT FOR SQUIRRELS (DIMENSIONLESS)
    TTHS   - TABLE TYPE HABITAT SQUIRRELS
    PO8M   - PROPORTION OF AREA IN POLE-8,POLE-10 AND
             MATURE HABITATS (PERCENT)

SDT.K=TABHL(TSDT,POG.K,0,.3,.1)                            76, S
TSDT=.1/.7/.8/1                                            76.1, T
    SDT    - SQUIRREL DEN TREE INDEX (DIMENSIONLESS)
    TSDT   - TABLE SQUIRREL DEN TREE
    POG    - PROPORTION OF AREA IN OLD GROWTH HABITAT
             (PERCENT)
```

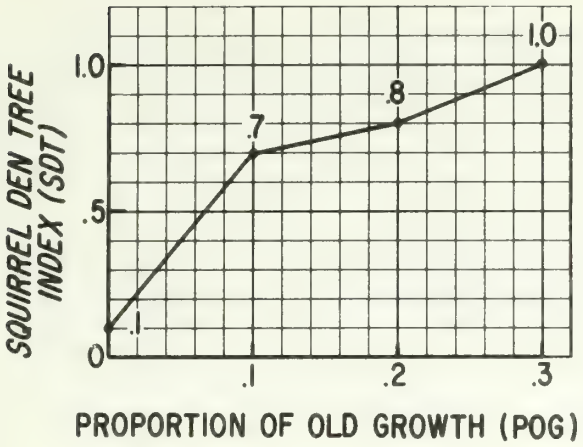


Figure 25.--Squirrel den tree index versus the proportion of area in old-growth habitat.

6.8 Turkey Habitat Index (TUR)

A primary winter food of turkeys is hard mast. During the warm months, openings produce much of the insects, soft mast, and other foods needed. Openings also serve as breeding, nesting, and brooding areas. These are the two important components of this index.

```
TUR.K=TURT.K*TURO.K                                          77, S
     TUR    - TURKEY HABITAT INDEX (DIMENSIONLESS)
     TURT   - TURKEY TYPE HABITAT (DIMENSIONLESS)
     TURO   - TURKEY OPENING INDEX (DIMENSIONLESS)

TURT.K=TABHL(TTRT,PO8M.K,0,.5,.1)                            78, S
TTRT=0/.1/.2/.5/.8/1                                         78.1, T
     TURT   - TURKEY TYPE HABITAT (DIMENSIONLESS)
     TTRT   - TABLE TURKEY TYPE
     PO8M   - PROPORTION OF AREA IN POLE-8,POLE-10 AND
              MATURE HABITATS(PERCENT)

TURO.K=TABHL(TTRO,OPS.K,0,28,2)                              79, S
TTRO=0/.2/.5/.7/.9/1/1/1/1/.9/.8/.7/.6/.5/.4                 79.1, T
     TURO   - TURKEY OPENING INDEX (DIMENSIONLESS)
     TTRO   - TABLE TURKEY OPENINGS
     OPS    - OPENING SIZE DISTRIBUTION (PROPORTIONAL
              AREA)
```

The index for turkey-type habitat (TURT) increases as the proportion of area in mast-producing trees (PO8M) increases (fig. 7, sec. 3.4). The limit is assumed to be when 50 percent of the area is in 8- and 10-inch poles and mature timber.

The ideal size of openings for turkeys is not known. The amount of marginal area is probably more important than the amount of total area in seedling habitats. Feeding, nesting, and often roosting seem to be associated with the transition area across the margin of openings. The algorithm assumes that turkeys benefit when harvest patterns create a maximum amount of usable margin for a given rate of timber harvest. According to the literature (Halls 1975), turkeys apparently use the margins of any size opening and go into the interior of pastures, fields, and forest clearings that are as large as 15 to 20 acres. In the index, openings of

10 to 15 acres are considered optimum because they provide large transitional areas and are small enough for turkeys to use most of the interior area (fig. 8, sec. 3.4). Smaller or larger openings are assumed to limit one or more habitat requirements.

6.9 Grouse Habitat Index (GRS)

Grouse inhabit thickets and brushland. They feed on browse at all seasons and require dense cover for escape, nesting, brooding, and winter protection. Thus, the index is based on the variety and interspersion of early stages of succession, as indicated by the proportion of total area in 6-inch pole stands and the frequency and size of openings. The proportion of pole-6 stands is a good indicator of seedling and sapling habitats as well.

```
GRS.K=GRH.K*GRO.K                                          80, S
    GRS    - GROUSE HABITAT INDEX (DIMENSIONLESS)
    GRH    - GROUSE HABITAT TYPE (DIMENSIONLESS)
    GRO    - GROUSE OPENING TYPE (DIMENSIONLESS)

GRH.K=TABHL(TGRH,PP6.K,0,.2,.05)                           81, S
TGRH=0/.2/.7/.9/1                                          81.1, T
    GRH    - GROUSE HABITAT TYPE (DIMENSIONLESS)
    TGRH   - TABLE GROUSE HABITAT
    PP6    - PROPORTION OF AREA IN POLE-6 HABITAT
             (PERCENT)

GRO.K=TABHL(TGRO,OPS.K,0,60,6)                             82, S
TGRO=.8/.9/.95/1/.95/.9/.85/.8/.7/.6/.5                    82.1, T
    GRO    - GROUSE OPENING TYPE (DIMENSIONLESS)
    TGRO   - TABLE GROUSE OPENINGS
    OPS    - OPENING SIZE DISTRIBUTION (PROPORTIONAL
             AREA)
```

As the proportion of area in 6-inch pole habitat increases to 20 percent, the index for grouse habitat type (GRH) increases to 1 (fig. 26). For a given area in 6-inch pole habitats, the size and frequency of openings affect the opportunity for use by the grouse. The index for grouse openings (GRO) increases as the size of openings decreases and their dispersion increases (fig. 27). These changes are indicated by the distribution of opening sizes (OPS).

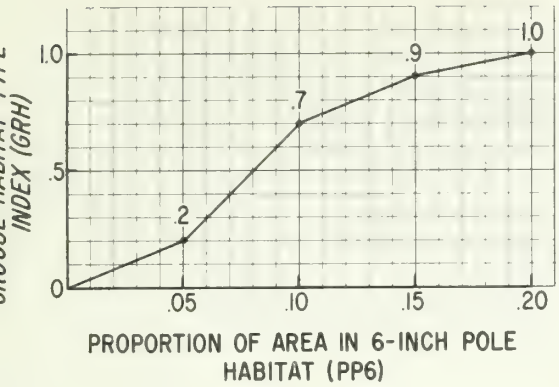
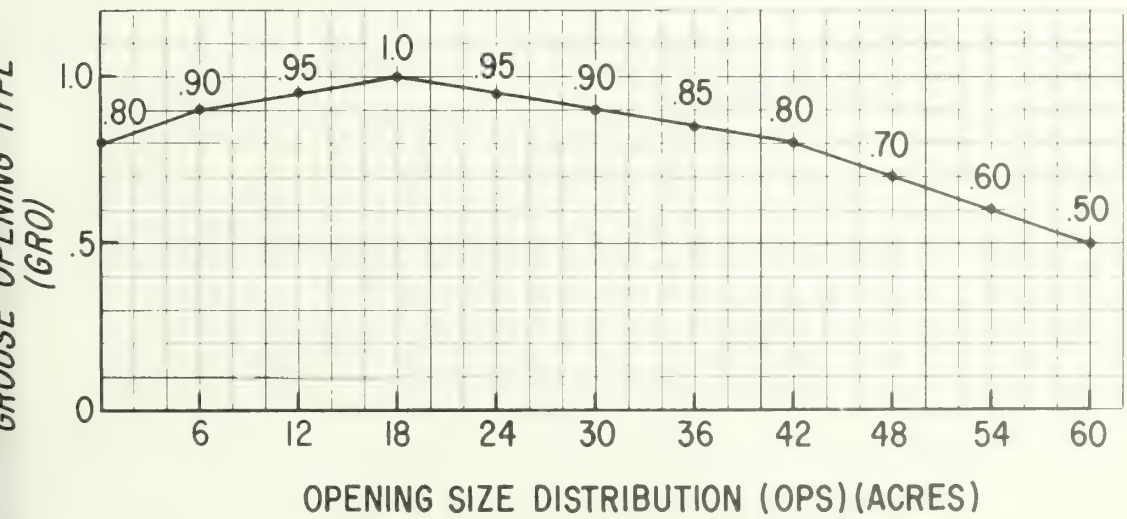


Figure 26.--Grouse habitat type index versus the proportion of area in 6-inch pole habitat.



igure 27.--Grouse opening type versus the distribution of size of openings (OPS).

6.10 Black Bear Habitat Index (BEAR)

Bears are omnivorous, using food from a variety of habitats at different times of the year. During the fall, they need large quantities of hard mast, and in the spring and warm months they feed on soft mast, grubs, insects, and small animals from seedling habitats. Bears use dense thickets for cover, and log and tree cavities for winter dens. The index includes habitat combinations that enhance these requirements for black bear.

```
BEAR.K=BDT.K*BSMT.K*BHMT.K                                    83, S
     BEAR   - BEAR HABITAT INDEX (DIMENSIONLESS)
     BDT    - BEAR DEN HABITAT (DIMENSIONLESS)
     BSMT   - BEAR SOFT MAST TYPE (DIMENSIONLESS)
     BHMT   - BEAR HARD MAST TYPE (DIMENSIONLESS)

BDT.K=TABHL(TBDT,POG.K,0,.3,.1)                               84, S
TBDT=.2/.8/.9/1                                               84.1, T
     BDT    - BEAR DEN HABITAT (DIMENSIONLESS)
     TBDT   - TABLE BEAR DEN TYPE
     POG    - PROPORTION OF AREA IN OLD GROWTH HABITAT
              (PERCENT)

BSMT.K=TABHL(TBSM,PSEA.K,0,.2,.1)                             85, S
TBSM=0/.5/1                                                   85.1, T
     BSMT   - BEAR SOFT MAST TYPE (DIMENSIONLESS)
     TBSM   - TABLE BEAR SOFT MAST
     PSEA   - PROPORTION OF AREA IN SEEDLINGS AND
              SAPLINGS (PERCENT)

BHMT.K=TABHL(TBHM,PO8M.K,0,.4,.1)                             86, S
TBHM=0/.2/.4/.8/1                                             86.1, T
     BHMT   - BEAR HARD MAST TYPE (DIMENSIONLESS)
     TBHM   - TABLE BEAR HARD MAST
     PO8M   - PROPORTION OF AREA IN POLE-8,POLE-10 AND
              MATURE HABITATS(PERCENT)
```

Small areas of old-growth habitat, if well distributed and protected from disturbance, can provide enough cavities for winter dens. Den requirements are assumed to be satisfied when about 10 percent of the total area is in old-growth habitat (fig. 28). A decline in old growth below 10 percent rapidly reduces the probability of tree dens being present. This index for dens (BDT) has a base of 0.2 because some winter dens are in rock cavities, windfalls, and dense thickets.

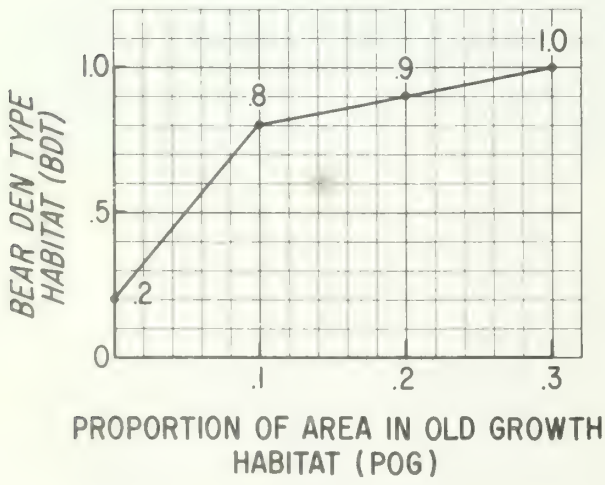


Figure 28.--Bear den type habitat versus the proportion of area in old growth.

Spring and summer foods and cover depend on the proportion of seedling and sapling habitats (fig. 29). The supply of hard mast is indicated by the proportion of area in 8-inch and 10-inch poles and mature timber (fig. 30). Of the three components of the index, hard mast is possibly the most restrictive. This index declines rapidly when the proportion of mast-producing habitats declines below 30 percent.

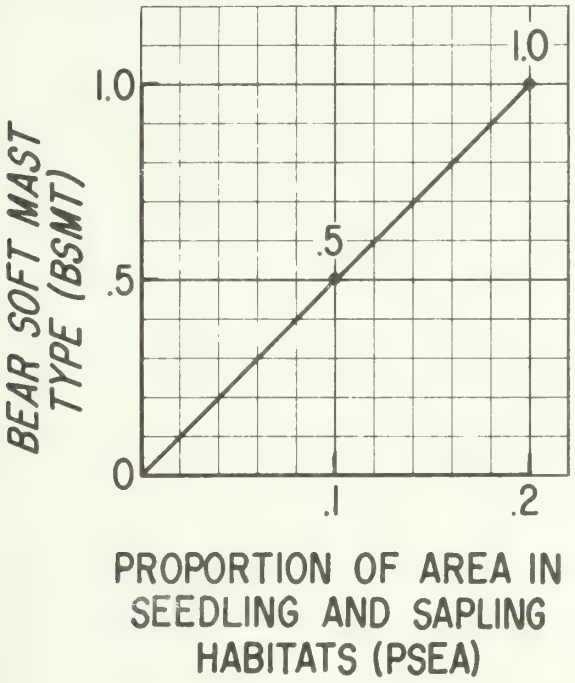


Figure 29.--Index of habitats for soft mast for bear versus the proportion of area in seedlings and saplings.

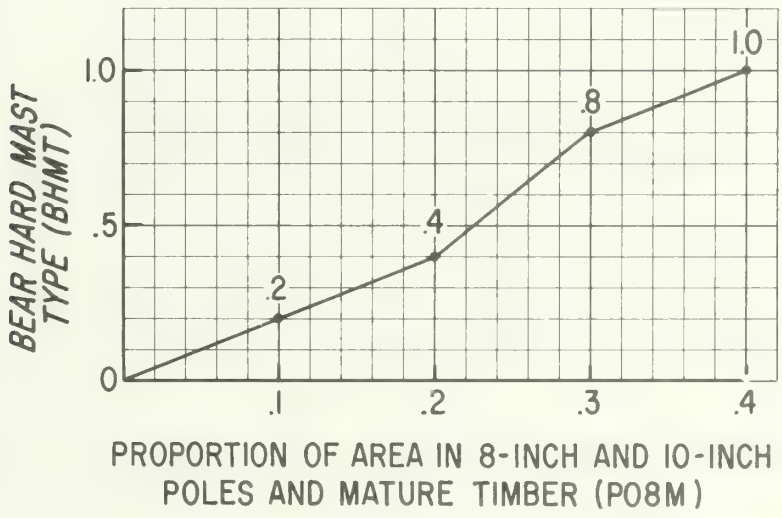


Figure 30.--Index of hard mast for black bear versus the proportion of area in mast-producing habitats.

6.11 Indices for Four Woodpeckers (PIL, FLIC, HAR, DON)

The nesting and habitat requirements for four woodpeckers are described by Conner and Adkisson (1976) and Conner and others (1975). These reports discuss the relative attractiveness of different habitats to these birds. As the proportional distribution of habitats changes, the index of attractiveness for each bird to the overall area varies. The authors suggest that the choice of habitat for nesting depends more on the prevalence of a habitat than on the woodpecker's preference. This question can be resolved by continuing to monitor the preference of these birds for habitats in relation to the distribution of habitats. The indices are to be adjusted as new data become available.

```
PIL.K=TABHL(TPIL,POG.K,0,.6,.1)                          87, S
TPIL=.1/.4/.6/.8/.9/.95/1                                87.1, T
     PIL    - PILEATED WOODPECKER HABITAT INDEX
              (DIMENSIONLESS)
     TPIL   - TABLE PILEATED WOODPECKER
     POG    - PROPORTION OF AREA IN OLD GROWTH HABITAT
              (PERCENT)

HAR.K=TABHL(THAR,PMO.K,0,.5,.05)                         88, S
THAR=.05/.1/.15/.2/.35/.5/.65/.8/.9/.95/1                88.1, T
     HAR    - HAIRY WOODPECKER HABITAT INDEX
              (DIMENSIONLESS)
     THAR   - TABLE HAIRY WOODPECKER
     PMO    - PROPORTION OF AREA IN MATURE AND OLD GROWTH
              HABITATS (PERCENT)

DON.K=TABHL(TDON,P1M.K,0,.4,.05)                         89, S
TDON=.1/.15/.3/.4/.6/.8/.9/.95/1                         89.1, T
     DON    - DOWNY WOODPECKER HABITAT INDEX
              (DIMENSIONLESS)
     TDON   - TABLE DOWNY WOODPECKER
     P1M    - PROPORTION OF AREA IN POLE-10 AND MATURE
              HABITATS (PERCENT)

FLIC.K=FLF.K*FLN.K*FLO.K                                 90, S
     FLIC   - FLICKER WOODPECKER HABITAT INDEX
              (DIMENSIONLESS)
     FLF    - FLICKER FOOD HABITAT (DIMENSIONLESS)
     FLN    - FLICKER NESTING HABITAT (DIMENSIONLESS)
     FLO    - FLICKER OPENING HABITAT (DIMENSIONLESS)

FLF.K=TABHL(TFLF,PSE.K,0,.06,.01)                        91, S
TFLF=.05/.15/.3/.5/.7/.9/1                               91.1, T
     FLF    - FLICKER FOOD HABITAT (DIMENSIONLESS)
     TFLF   - TABLE FLICKER FOOD
     PSE    - PROPORTION OF AREA IN SEEDLING HABITAT
              (PERCENT)

FLN.K=TABHL(TFLN,PMO.K,0,.2,.05)                         92, S
TFLN=.5/.8/.9/.95/1                                      92.1, T
     FLN    - FLICKER NESTING HABITAT (DIMENSIONLESS)
     TFLN   - TABLE FLICKER NESTING
     PMO    - PROPORTION OF AREA IN MATURE AND OLD GROWTH
              HABITATS (PERCENT)
```

```
FLC.K=TABHL(TFLO,OPS.K,0,10,2)                          93, S
TFLC=.05/.1/.5/.9/.95/1                                 93.1, T
     FLO     - FLICKER OPENING HABITAT (DIMENSIONLESS)
     TFLO    - TABLE FLICKER OPENING
     OPS     - OPENING SIZE DISTRIBUTION (PROPORTIONAL
               AREA)
```

The index for pileated woodpeckers is based on the proportion of area in old-growth habitat (POG, fig. 31).

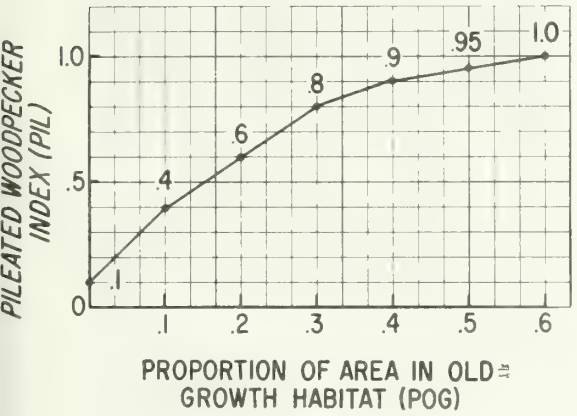


Figure 31.--Index of pileated woodpecker habitat versus the proportion of area in old-growth habitat.

The index for hairy woodpeckers is based on the proportion of area in mature and old-growth habitats (PMO, fig. 32).

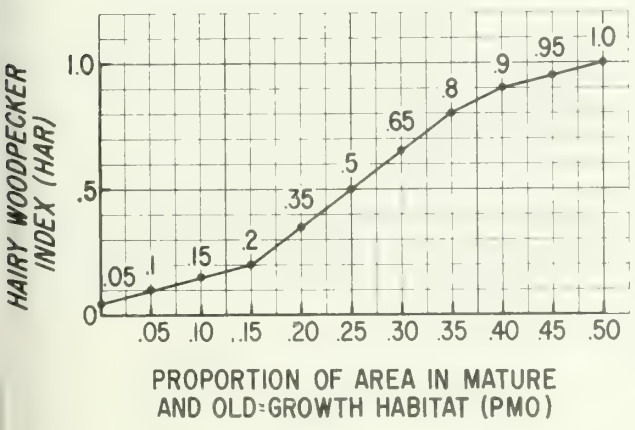


Figure 32.--Index for hairy woodpecker habitat versus the proportion of area in mature and old-growth habitats.

The index for downy woodpeckers is based on the proportion of area in pole-10 and mature timber habitats (PIM, fig. 33).

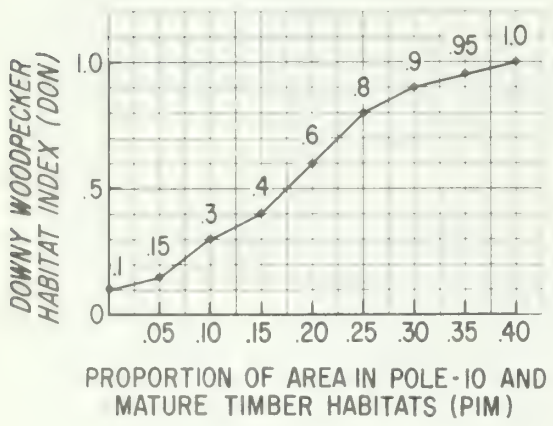


Figure 33.--Index of downy woodpecker habitat versus the proportion of area in pole-10 and mature timber habitats.

The index for the common flicker is more complex and is related to the proportion of area in seedling habitat (PSE, fig. 34), mature and old-growth habitats (PMO, fig. 35), and the distribution of opening sizes (OPS, fig. 36). Flickers often nest in rotting snags left in seedling and sapling habitats. These habitats also provide food for flickers. The proportion of area in mature and old growth is of minor importance if snags are left in seedling habitats. However, the fast mode of management limits the probability that snags will occur in the borders of seedling habitats because mature timber habitats are harvested with only a year or two delay (DMT, table 1). Thus, the proportion of mature and old-growth habitats is an important component of the flicker index.

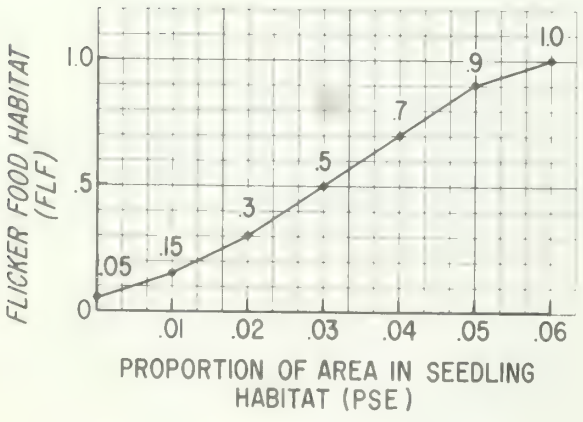


Figure 34.--Flicker food habitat index versus the proportion of area in seedling habitat.

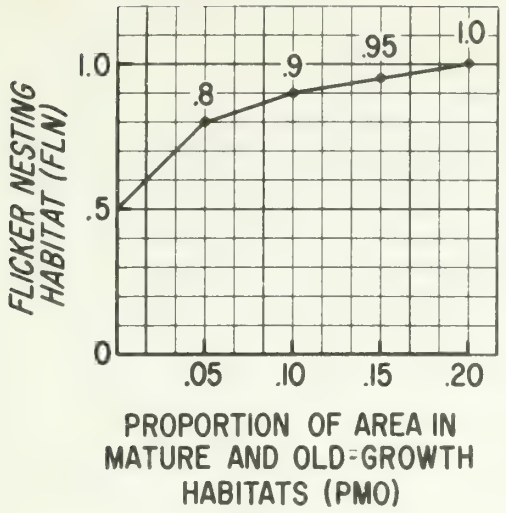


Figure 35.--Flicker nesting habitat versus the proportion of area in mature and old-growth habitats.

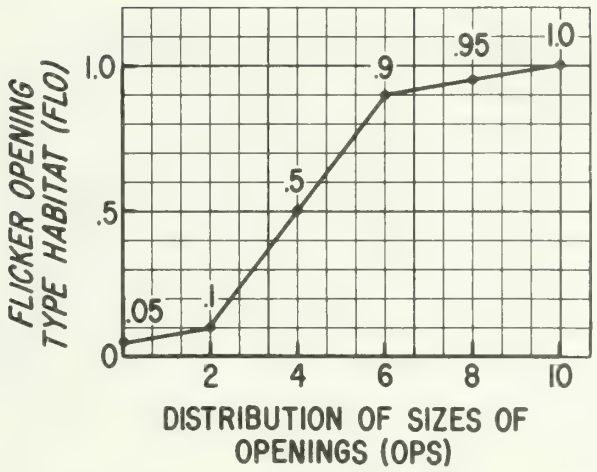


Figure 36.--Flicker opening type habitat versus the opening size distribution.

```
TWE.K=TWH.K*TWO.K                                          98, S
     TWE     - TOWHEE HABITAT INDEX (DIMENSIONLESS)
     TWH     - TOWHEE HABITAT TYPE (DIMENSIONLESS)
     TWO     - TOWHEE OPENING TYPE (DIMENSIONLESS)

TWH.K=TABHL(TTWH,PSA.K,0,.45,.05)                          99, S
TTWH=0/.1/.2/.4/.6/.8/.85/.9/.95/1                         99.1, T
     TWH     - TOWHEE HABITAT TYPE (DIMENSIONLESS)
     TTWH    - TABLE TOWHEE HABITAT
     PSA     - PROPORTION OF AREA IN SAPLING HABITAT
               (PERCENT)

TWO.K=TABHL(TTWO,OPS.K,0,5,1)                              100, S
TTWO=.1/.5/.7/.8/.9/1                                      100.1, T
     TWO     - TOWHEE OPENING TYPE (DIMENSIONLESS)
     TTWO    - TABLE TOWHEE OPENING
     OPS     - OPENING SIZE DISTRIBUTION (PROPORTIONAL
               AREA)

PWE.K=TABHL(TPWE,PMO.K,0,.7,.1)                            101, S
TPWE=.1/.2/.4/.7/.8/.9/.95/1                               101.1, T
     PWE     - PEEWEE HABITAT INDEX (DIMENSIONLESS)
     TPWE    - TABLE PEEWEE HABITAT
     PMO     - PROPORTION OF AREA IN MATURE AND OLD GROWTH
               HABITATS (PERCENT)
```

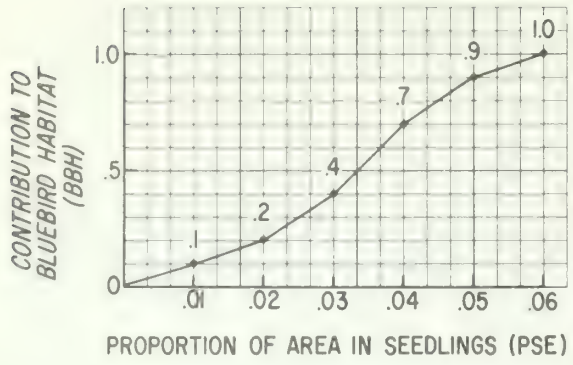


Figure 37.--Bluebird habitat index versus the proportion of area in seedling habitat.

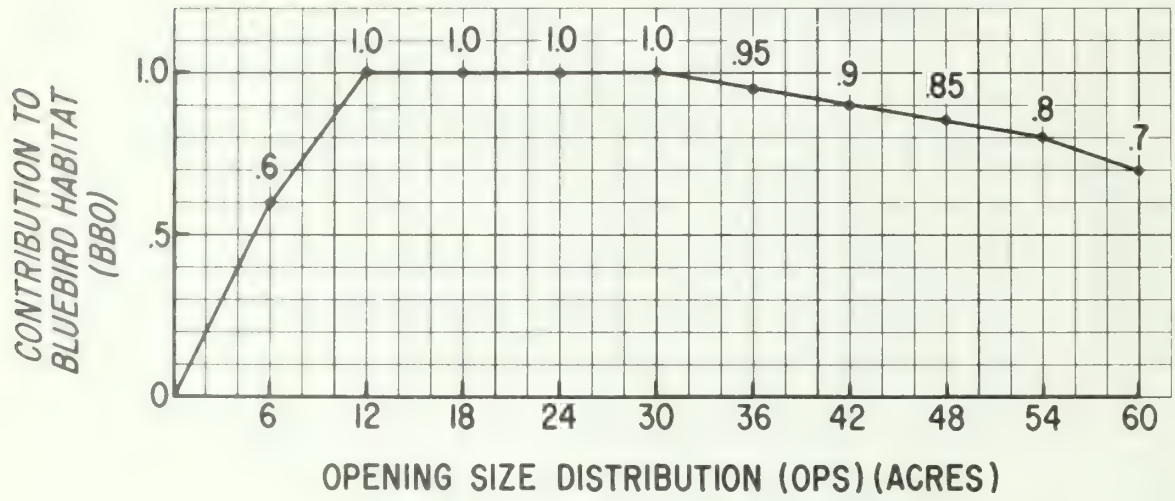


Figure 38.--Bluebird habitat index versus the distribution of size of openings.

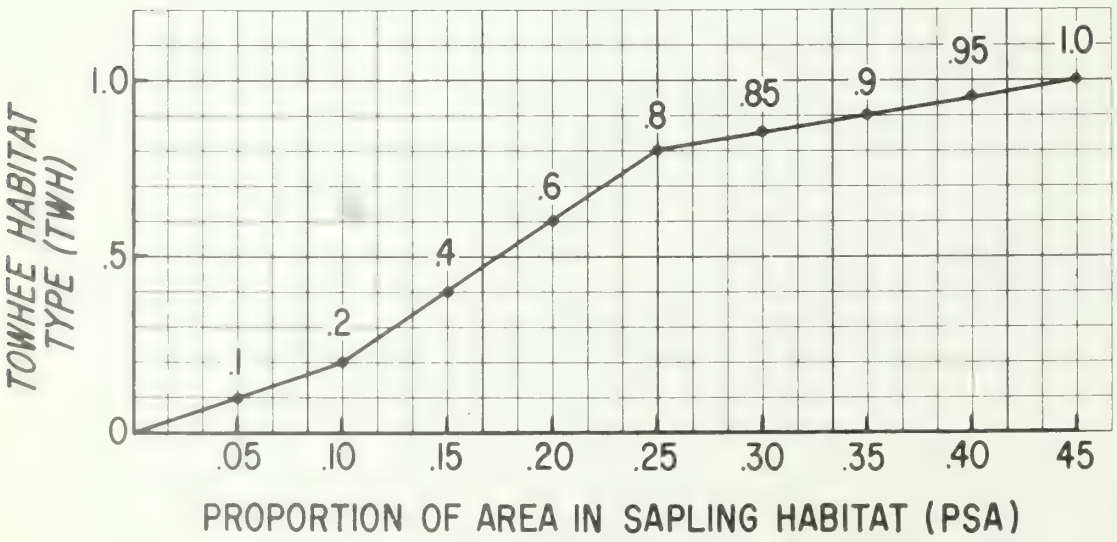


Figure 39.--Index of towhee habitat type versus the proportion of area in sapling habitat.

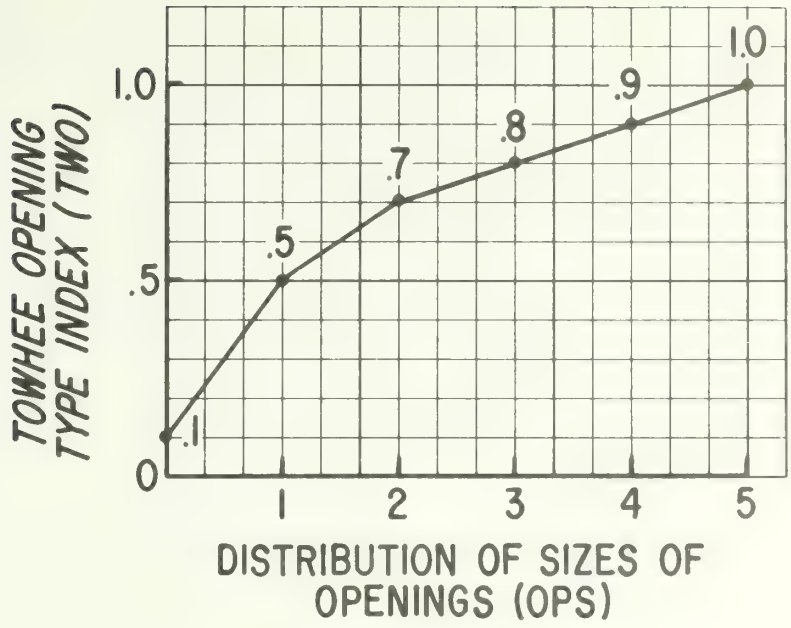


Figure 40.--The opening index for towhee habitat versus the distribution of size of openings.

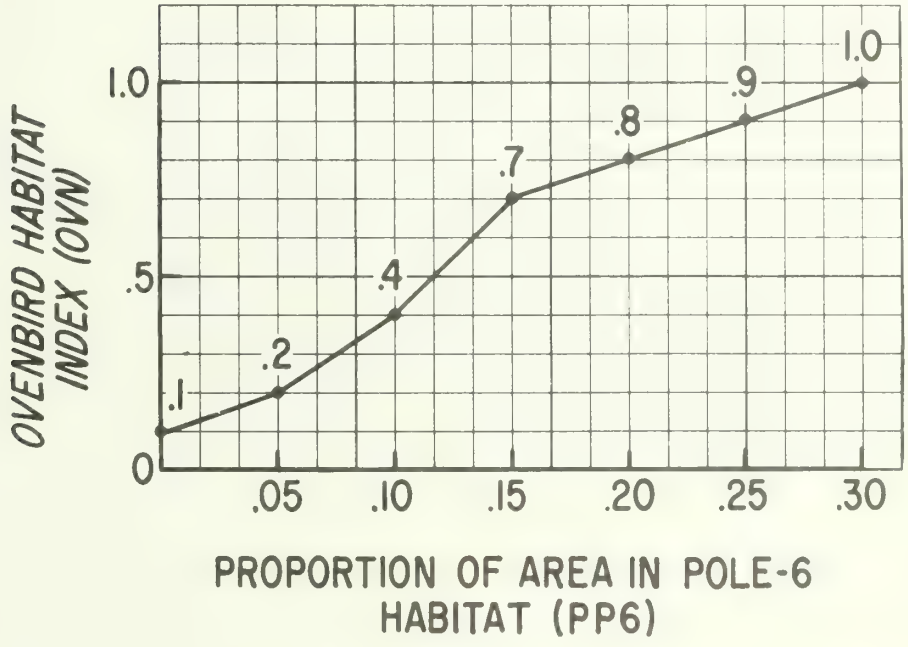


Figure 41.--Ovenbird habitat index versus the proportion of area in pole-6 habitat.

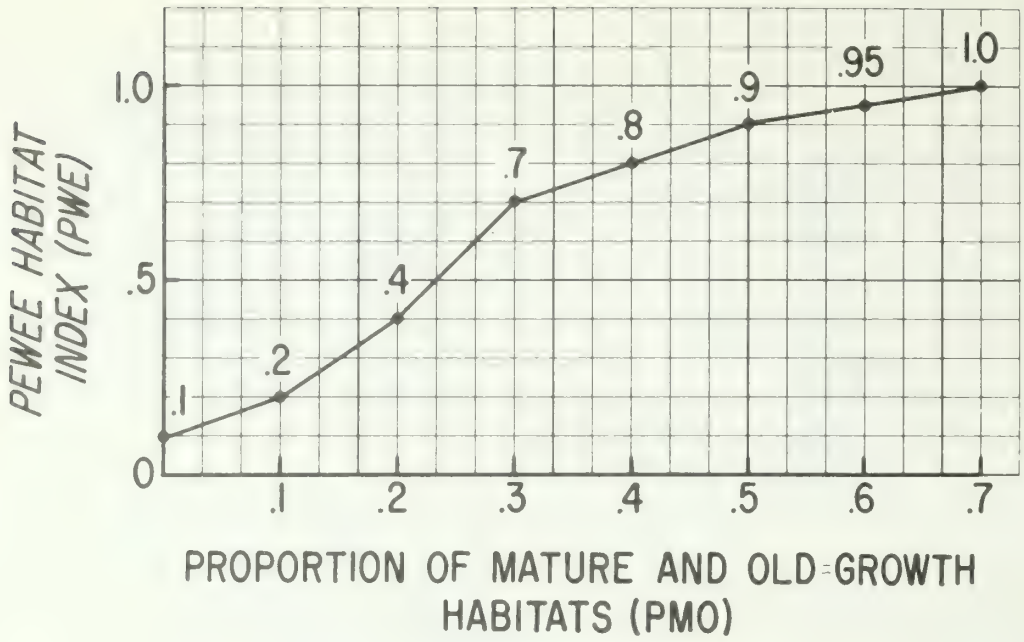


Figure 42.--Pewee habitat index versus the proportion of area in mature and old-growth habitats.

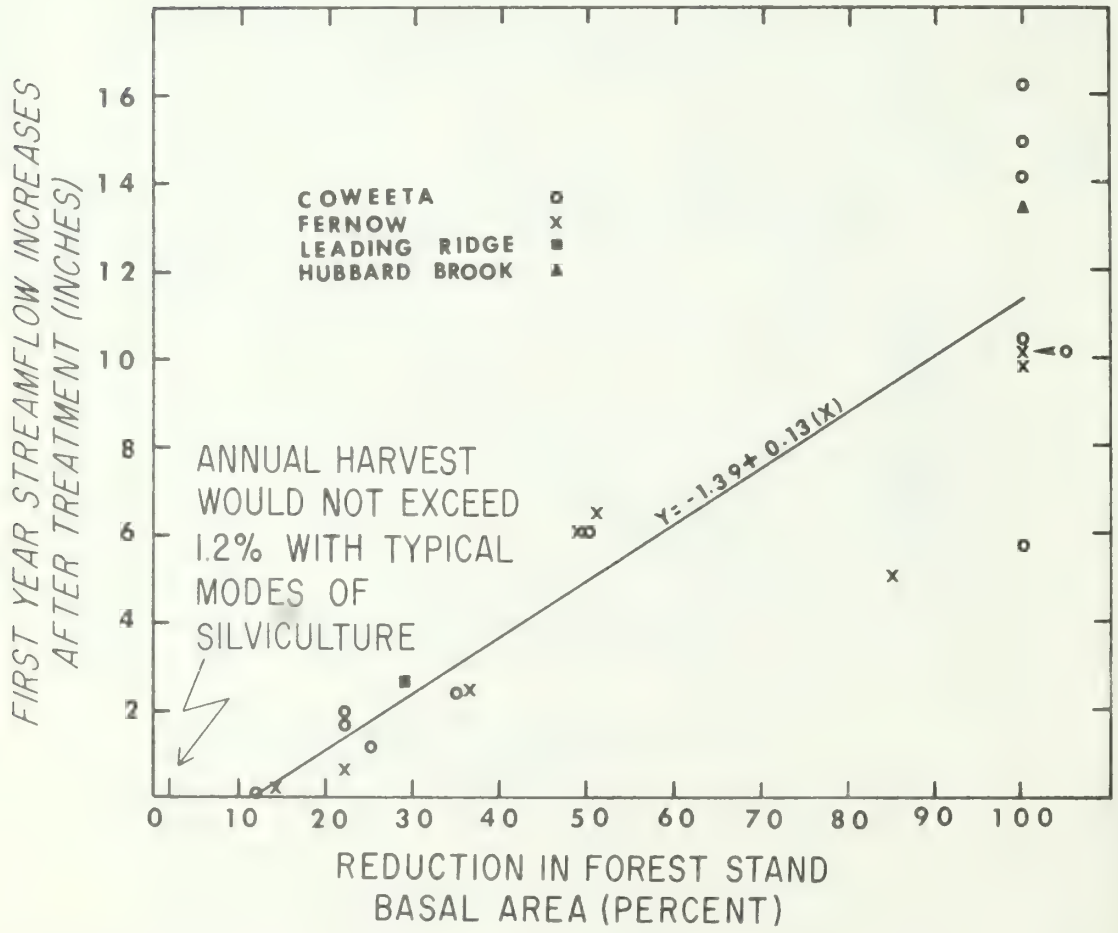


Figure 43.--Relationship between streamflow increase the first year after forest removal and the percentage reduction in forest stand (from Douglass and Swank 1972).

6.12 Indices for Four Groups of Birds (BLU, TWE, OVN, PWE)

The indices for four songbirds are based on the frequency of their occurrence in different habitats, as reported by Conner and Adkisson (1975) and other sources. Each of the four species represents a group of birds with a preference for a type of forest habitat: the eastern bluebird (BLU) for seedling habitat, the rufous-sided towhee (TWE) for sapling habitat, the ovenbird (OVN) for 6-inch pole timber, and the eastern wood pewee (PWE) for mature and old-growth habitat.

The bluebird-group index varies with the proportion of area in seedling habitat and the opening size distribution (figs. 37 and 38). The towhee-group index is based on the proportion of area in sapling habitats (fig. 39). Size of opening is considered important for this group of birds but limited information is available (fig. 40). The ovenbird-group index is based on the proportion of area in pole-6 habitat (fig. 41) and probably should have included a variable for size of opening.

The index for the pewee group of birds is based on the proportion of area in mature and old-growth habitats (fig. 42). The size of openings affects the physical structure of succeeding habitats, especially the old-growth habitats. This probably affects the quality of bird habitat at all stages of succession (MacArthur and MacArthur 1961). More information on these relationships could improve the indices for songbirds.

```
BLU.K=BBH.K*BBO.K                                          94, S
     BLU    - BLUEBIRD HABITAT INDEX (DIMENSIONLESS)
     BBH    - BLUEBIRD HABITAT TYPE (DIMENSIONLESS)
     BBO    - BLUEBIRD OPENING TYPE (DIMENSIONLESS)

BBH.K=TABHL(TBBH,PSE.K,0,.06,.01)                          95, S
TBBH=0/.1/.2/.4/.7/.9/1                                    95.1, T
     BBH    - BLUEBIRD HABITAT TYPE (DIMENSIONLESS)
     TBBH   - TABLE BLUEBIRD HABITAT
     PSE    - PROPORTION OF AREA IN SEEDLING HABITAT
              (PERCENT)

BBO.K=TABHL(TBBO,OPS.K,0,60,6)                             96, S
TBBO=0/.6/1/1/1/1/.95/.9/.85/.8/.7                         96.1, I
     BBO    - BLUEBIRD OPENING TYPE (DIMENSIONLESS)
     TBBO   - TABLE BLUEBIRD OPENING
     OPS    - OPENING SIZE DISTRIBUTION (PROPORTIONAL
              AREA)


OVN.K=TABHL(TOVN,PP6.K,0,.3,.05)                           97, S
TOVN=.1/.2/.4/.7/.8/.9/1                                   97.1, T
     OVN    - OVENBIRD HABITAT INDEX (DIMENSIONLESS)
     TOVN   - TABLE OVENBIRD
     PP6    - PROPORTION OF AREA IN POLE-6 HABITAT
              (PERCENT)
```

6.13 Waterflow

Because no measurably increased flows of water are expected from typical modes of multiple-benefit management, no index of change is included in the management system.

Forests delay the flow of water through the landscape by intercepting rainfall, storing water in plant tissues, and building absorptive soils. They divert some water back to the atmosphere by transpiration.

Removing the forest reduces the delays and increases the total streamflow (Worley and Patric 1971; Douglass and Swank 1972; Husch and others 1972; Douglass 1974). The amount and duration of an increase in streamflow can be estimated from how much of the watershed is harvested, the amount of insolation, and the increase in flow from the harvested area the first year (Douglass and Swank 1975). Harvesting the entire watershed may increase flows by 8 to 18 inches[3/] the first year. However, flows rapidly decrease during the seedling habitat stage. Soon after the stands enter the sapling stage, streamflows subside to the levels before harvest.

For increases in streamflow to be measurable, 10 percent or more of the basal area in a watershed must be removed (fig. 43) (Douglass and Swank 1972). A particular opening of 25 acres may cause an increased flow for 5 to 10 years, but if this opening represents less than 10 percent of the managed area, very little if any measurable increase can be expected in waterflow from the total area. The fastest rate of harvest considered in the examples (table 1) is a rotation period of 86 years and amounts to an annual harvest of about 1.2 percent of the managed area per year. If investigations of managed areas show that changes in streamflow exceed those found in studies of small watersheds, then appropriate algorithms can be developed.

One variable for which we need information is the effect of roads and skid trails on the flow of water to streams. With appropriate data, algorithms could be developed to relate the size and frequency of openings to flows of water, nutrients, and other materials, as illustrated for the sediment index (sec. 2.2).

6.14 Nutrient Flow

At present, we do not know enough about nutrient flows to develop an index.

Forests delay the flows of nutrients through the landscape. The delays are reduced by the removal of trees and by increased movement of sediment. We do not know how many nutrients are lost immediately after harvest or how many are replaced before the next harvest. These questions are being investigated by many workers (Howell and others 1975). Appropriate indices can be developed when data become available.

3/ One inch of increase in streamflow equals the volume of water required to cover the watershed to a depth of 1 inch.

The removal of wood from a forest necessarily removes some nutrients from the area. Losses are generally proportional to the amount of wood removed, but may vary with the kind of soil and the size of the woody materials. Removing leaves, roots, and small branches may remove more nutrients per unit weight of organic matter than the removal of large logs (Stone 1975; Patric and Smith 1975; Douglass and Swank 1976).

According to the preliminary information we have, the rates of harvest considered for DYNAST-MB (table 1) would not increase nutrient flows enough to limit future timber yields, degrade drinking water, or harm the biological productivity of streams (Douglass and Swank 1975).

More information might allow us to regulate distribution of forest habitats for desirable flows of nutrients and organic matter through streams. Energy and nutrients from leaves, branches, roots, and similar terrestrial organic matter are the primary sources of support for animals in many streams (Howell and others 1975). However, our knowledge about the delays in the flow of energy and material comes from small watersheds that are in a single state of organization. These studies are incomplete in that the kinds and amounts of delay are known for only a few habitats. Because of this lack of knowledge, the productivity of streams cannot be purposively influenced by regulating the combination of habitats in watersheds. When more knowledge is available, algorithms can be developed for the productivity of streams in the same way as for the potential timber index (sec. 6.2).

7. THE DYNAMICS OF SIX MODES OF MANAGEMENT: AN APPALACHIAN EXAMPLE

This section analyzes the model runs for six modes of management (table 1) applied to the Big Ivy watershed in North Carolina. A user may work from these illustrations to develop some intermediate modes that would be suitable for a similar area. Each mode is illustrated by one table and three computer plots. These illustrations are not described separately, since they have the same format. The variables are defined in appendix B and on the control cards which have the equation numbers 105.1 through 106.3.

The first line at the top of each table or plot identifies the program, DYNAST-MB; the area, unit 16, Big Ivy, standard lands; the date and time the model was run, 1/05/77, 19:18; and the mode of management, as described in table 1. For example, FAST 45/10 is the fast rate of harvest with openings in mature timber of 45 $\pm$ 4.4 acres and openings in old-growth timber of 10 $\pm$ 2.4 acres. The page numbers are simply the sequence of printing by the computer.

The second and third lines in the tables name the variables; the third and fourth lines indicate the location of decimal points. For example, E + 03 means the number should be multiplied by 10^3. The first column in the tables is time in years. Data are printed annually for the first 10 years, then at 40-year intervals.

The second line on the plots lists the variables and the symbols used in the plot. The scales for the plots are indicated in the next one or more lines. For example, the plots for the proportional distribution of habitats have three scales. The proportion of seedling habitats is plotted on a scale of 0 to 10 percent. The proportion of saplings, pole-6, pole-8, and pole-10 habitats is plotted on a scale of 0 to 40 percent. The proportion of mature and old-growth habitats is scaled from 0 to 80 percent. All of the benefit and impact plots are scaled from 0 to 1.

Time in years is plotted at the bottom (first column) of the charts. The variables are plotted annually for the first 10 years and then at 4-year intervals. Time begins at the time of the inventory. The plotted 170-year period is enough time for the faster rates of harvest to bring the distribution of habitats and the indices for benefits to a steady state, although the salvage mode continues to oscillate for about 550 years. The 170-year period seems adequate for providing information.

Groups of letters above the chart show coincident indices. The first letter of each group appears on the plot; the other indices are at the same level as the plotted symbol. These groups must not be confused with indices at the top line (value 1) of the plot.

TIME	OGS VOG	MTS VMT	PTI VT	OG MT	P1 P8	P6 SA	SE SEMT	DEER SQU	TUR GRS	VIS UGL	BEAR PIL	FLIC DON	TWE NOP	OPM OPS
E+00	E+00 E+00	E+00 E+03	E+00 E+03	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00
.0	.95572 1867.7	94.043 191.07	.6514 192.94	185.96 460.04	1808.0 740.0	1843.0 1254.0	200.00 .32712	.33750 .27444	.37624 .74239	.42130 .28697	.37444 .18722	.47338 .95460	.58424 2.1794	.21808 45.457
1.	.95572 2699.6	92.281 254.66	.8690 257.36	185.40 494.60	1769.5 809.7	1763.9 1253.0	214.83 .39014	.38786 .27392	.38447 .77836	.44237 .31224	.37392 .18696	.51819 .95398	.58364 2.5993	.26009 43.298
2.	.95572 3325.1	89.131 304.72	1.0401 308.04	184.67 511.80	1737.2 869.9	1690.0 1256.1	241.34 .42026	.40064 .27324	.39010 .71198	.46945 .37274	.37324 .18662	.59501 .95162	.58556 2.8000	.28018 47.281
3.	.95572 4013.4	85.692 328.62	1.1231 332.63	183.85 519.55	1710.2 921.5	1621.0 1264.6	270.29 .37947	.44988 .27247	.39415 .72259	.47483 .46177	.37247 .18623	.67809 .94861	.59087 2.5282	.25298 46.644
4.	.95572 3947.4	82.533 336.84	1.1506 340.78	182.98 522.80	1687.7 965.4	1556.9 1278.4	296.87 .47562	.53009 .27165	.39723 .79369	.45085 .49191	.37165 .18582	.75404 .94560	.59950 3.1688	.31708 42.379
5.	.95572 4150.8	79.897 336.44	1.1500 340.59	182.07 524.43	1669.0 1002.3	1497.5 1296.7	319.05 .43270	.49603 .27079	.39972 .72094	.43046 .56618	.37079 .18540	.81729 .94293	.61093 2.8829	.28847 46.743
6.	.95572 4252.0	77.839 331.93	1.1351 336.19	181.14 526.00	1653.4 1033.2	1442.5 1318.4	336.38 .43411	.53364 .26992	.40000 .74611	.38984 .63045	.36992 .18496	.84311 .94075	.62450 2.8923	.28941 45.233
7.	.95572 4327.8	76.313 326.00	1.1154 330.33	180.20 528.21	1640.5 1058.5	1391.9 1342.4	349.22 .41592	.52584 .26904	.40000 .72156	.35887 .68945	.36904 .18452	.86158 .93908	.63955 2.7711	.27728 46.706
8.	.95572 4508.0	75.232 320.13	1.0961 324.64	179.25 531.30	1629.8 1079.0	1345.3 1368.0	358.32 .40354	.58590 .26815	.40000 .78110	.33675 .73181	.36815 .18408	.87485 .93789	.65550 2.6886	.26903 43.134
9.	.95572 4417.5	74.501 315.03	1.0786 319.45	178.30 535.24	1620.9 1095.2	1302.6 1394.2	364.48 .40143	.54588 .26726	.40000 .72755	.32149 .75709	.36726 .18363	.88408 .93710	.67191 2.6746	.26762 46.347
10.	.95572 4543.5	74.028 310.95	1.0653 315.50	177.35 539.89	1613.3 1107.7	1263.6 1420.6	368.45 .38425	.57906 .26637	.40000 .75726	.31131 .78325	.36637 .18318	.89031 .93665	.68844 2.5601	.25617 44.342
50.	.95572 4460.4	73.547 303.76	1.0407 308.22	139.12 614.10	1396.6 977.5	969.3 2021.6	372.51 .37542	.54658 .23051	.37377 .64971	.28338 .80487	.33051 .16526	.90162 .91438	.86608 2.5012	.25028 46.835
90.	.95572 4322.2	73.547 296.33	1.0152 300.66	100.89 381.07	1354.0 1037.1	1066.0 2179.1	372.51 .39067	.56232 .19465	.34675 .68810	.25106 .79524	.29465 .14732	.83574 .84256	.89070 2.6029	.26045 45.765
130.	.95572 4204.1	71.175 286.78	.9825 290.98	62.66 217.70	1424.0 1091.1	1103.1 2220.3	371.67 .38542	.54445 .15878	.34182 .67840	.23792 .79525	.25878 .12939	.74859 .81335	.89714 2.5679	.25695 46.925
170.	.95572 3999.8	73.141 289.40	.9906 293.39	24.43 220.31	1463.0 1103.3	1103.3 2206.6	369.51 .38881	.55463 .12292	.34855 .69165	.23443 .78460	.22292 .11146	.71333 .82637	.89499 2.5904	.25921 46.086

```
DYNAST-MB 16 B.IVY ST    1/06/77 19:51   FAST 45/10

PSE=S,PSA=A,PP6=6,PP8=8,PP1=1,PMT=M,POG=O

     .0          .025          .05          .075          .1 S
     .0           .1           .2            .3           .4 A681
     .0           .2           .4            .6           .8 MO
   .0- O -N- - - - - -8-S- - - - -A- - - - - - 16- - - - - - - - -
     . O   M        .   8S        A.           6   .              . 61
     . O   M        .    8  S     A.          61   .              .
     . O   M        .      8  S    A        6 1   .              .
     . O   M        .       8     S A      6  1   .              .
     . O   M        .        8      S    6    1    .              . SA
     . O   M        .        8      .AS 6     1    .              .
     . O   M        .          8    .A S      1    .              . S6
     . O   M        .          8    . A S     1    .              . A6
     . O   M        .           8   .6 AS     1    .              .
  10.- O - M - - - - - - - - - - 8 - 6 -A-S- 1 - - - - - - - - - - -
     . O     M      .           86   .    SA1      .              .
     . O     M      .          68    .     S 1A    .              .
     . O     M      .        6  8    .     S 1  A  .              .
     . O     M      .        6 8     .     S1    A .              .
     . O     M      .      6  8      .     S1      A.             .
     . O     M      .      6 8       .     S         A.           . S1
     . O     M      .      6 8       .    1S           A          .
     . O     M      .      68        .    1S           .A         .
     . O     M      .      68        .   1 S           . A        .
  50.- O - -M- - - - - - - -6- - - - -1-S- - - - - -A- - - - - - - 68
     . O     M      .        6       .  1  S          .  A         . 68
     . O     M      .        6       .  1  S          .   A        . 68
     .O      M      .        86      .  1  S          .   A        .
     .O      M      .        86      .  1  S          .   A        .
     .O      M      .        86      .  1  S          .    A       .
     .O      M      .         6      . 1   S          .    A       . 68
     .O    M        .         6      . 1   S          .    A       . 68
     .O    M        .         86     .  1  S          .     A      .
     .O    M        .         86     .  1  S          .     A      .
  90.-O-  M - - - - - - - - - - 86- - - 1 -S- - - - - - - -A- - - - -
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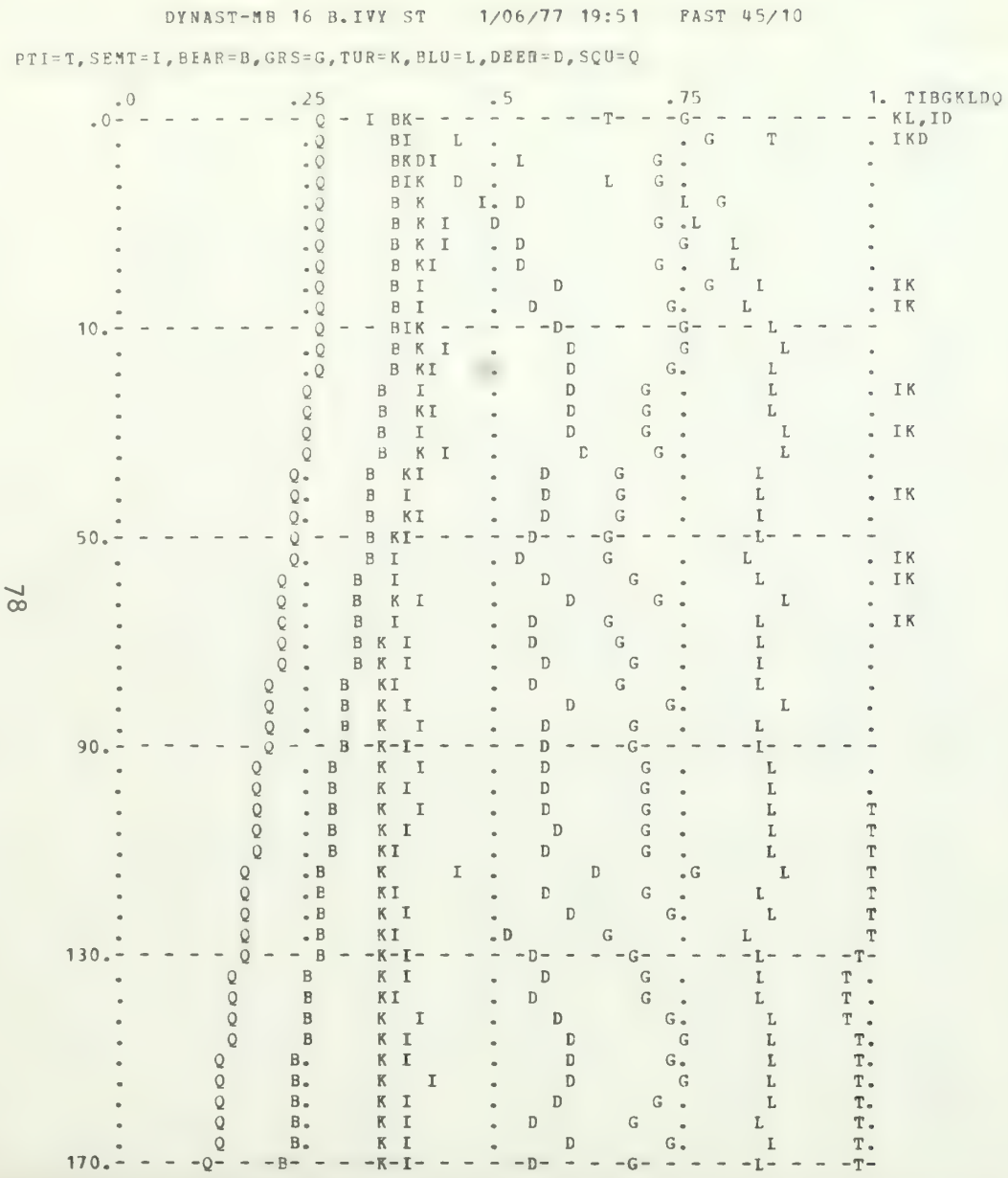
     .O    M        .          6     .  1  S          .      A     . 68
     .O  M          .          6     .  1  S          .      A     . 68
     .O  M          .          86    .   1 S          .      A     .
     .O  M          .          86    .   1 S          .      A     .
     .O  M          .          86    .   1 S          .      A     .
     .O  M          .          86    .   1 S          .      A     .
     .O  M          .           6    .   1 S          .      A     . 68
  130.-O-M- - - - - - - - - - - - 6 - - -1-S- - - - - - - - A - - - - 68
     .O  M          .           6    .    S           .      A     . 68,S1
     .O  M          .           6    .    S           .      A     . 68,S1
     .O  M          .           6    .    S           .      A     . 68,S1
     .O  M          .           6    .    S           .      A     . 68,S1
     .O  M          .           6    .    S           .      A     . 68,S1
     O   M          .           6    .    S           .      A     . 68,S1
     O   M          .           6    .    S           .      A     . 68,S1
     O   M          .           6    .   1S           .      A     . 68
     O   M          .           6    .   1S           .      A     . 68
  170.O -M- - - - - - - - - - - - 6 - - - 1S- - - - - - - - A - - - - 68
```

7.1 The Fast Mode (FAST)
(table 4 and figs. 44, 45, 46)

This mode produces timber at about the maximum. The lack of mast-producing habitats lowers the indices for squirrel, turkey, and bear. Indices for the pewee group of birds and for pileated and hairy woodpeckers are kept at a low level. Ugliness is relatively high, sediment is relatively low, and visual contrast is low.

Table 4.--Fast mode (FAST 45/10). Data for the control of timber sales and information about the volumes of timber removed, the distribution of habitats, the indices for some benefits, number of openings per square mile, and the distribution of opening sizes. For definitions see appendix B.

Figure 44.--Fast mode (FAST 45/10). The distribution of seedlings (S), saplings (A), 6-inch poles (6), 8-inch poles (8), 10-inch poles (1), mature timber (M), and old growth (O). Note the difference in scales which was necessary to illustrate the changes.


DYNAST-MB 16 B.IVY ST 1/06/77 19:51 FAST 45/10
PTI=T,SEMT=I,BEAR=B,GRS=G,TUR=K,BLU=L,DEER=D,SQU=Q
.0 .25 .5 .75 1. TIBGKLDQ
KL,ID
IKD
IK
IK
IK
IK
IK
IK
T
T
T

VIS=V,UGI=U,CVN=O,PIL=P,FLIC=F,DON=N,TWE=W,PWE=E,HAR=H

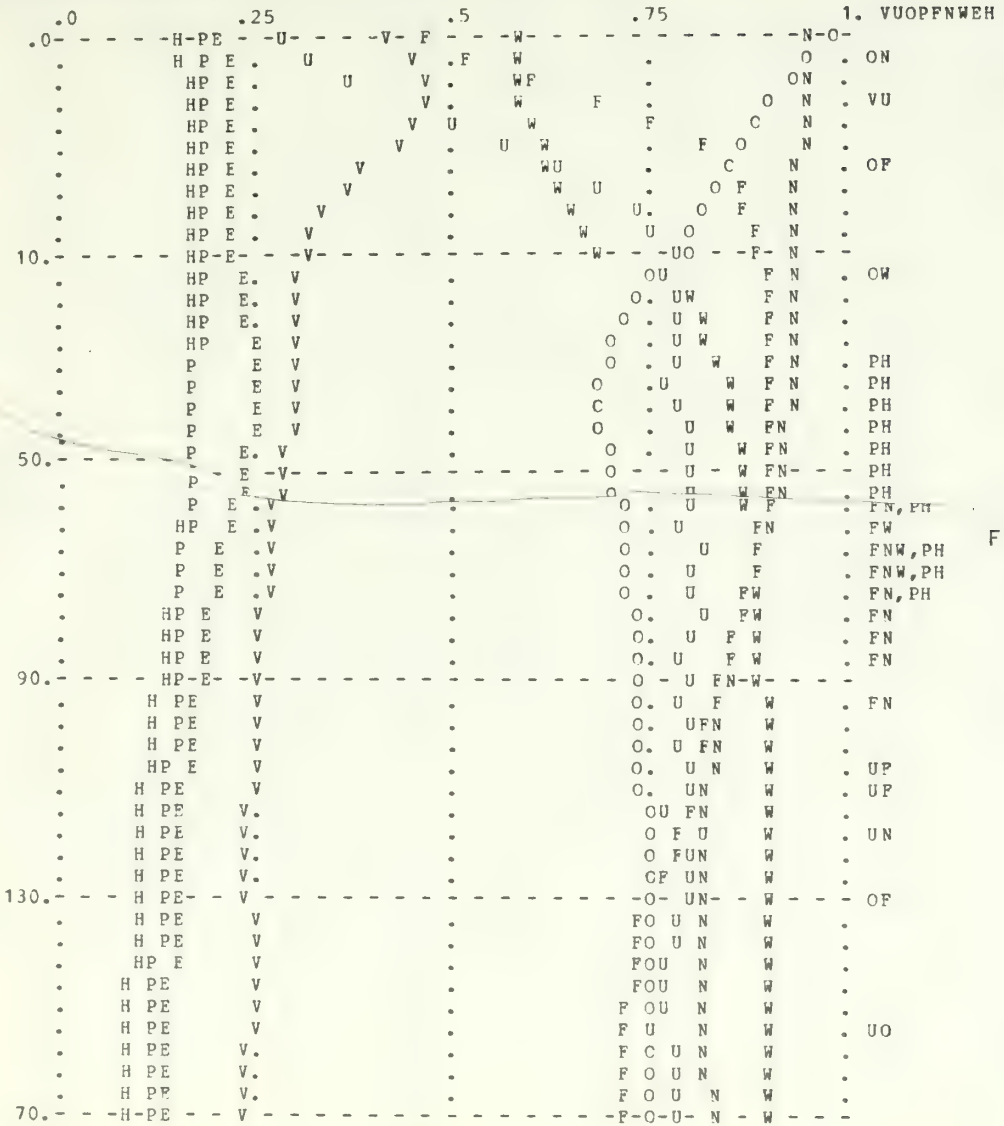
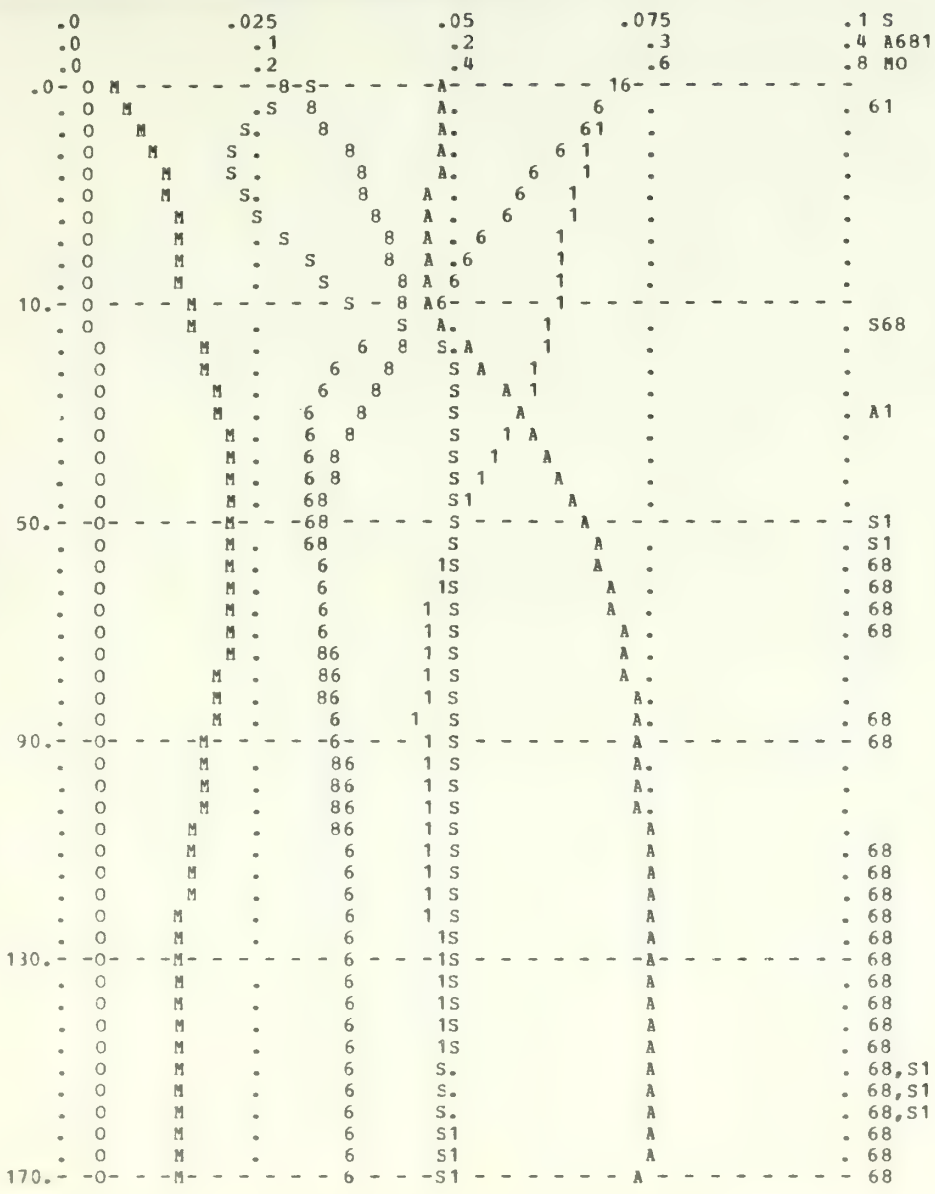


Figure 46.--Fast mode (FAST 45/10). Changes in the indices for visual variety (V), ugliness (U), ovenbird group (O), pileated woodpecker (P), flicker (F), downy (N), towhee group (W), pewee group (E), and hairy woodpecker (H).

TIME	OGS VOG	MTS VMT	PTI VT	OG MT	P1 P8	P6 SA	SE SEMT	DEER SQU	TUR GRS	VIS UGL	BEAR PIL	PLIC DON	TWE NOP	OPM OPS
E+00	E+00 E+03	E+00 E+03	E+00 E+03	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00
.0	1.6948 3.497	8.076 16.40	.06718 19.90	186.69 374.1	1808.0 740.0	1843.0 1254.0	200.00 .31845	.52539 .27514	.40321 .86014	.41464 .15321	.37514 .18757	.19395 .94116	.50295 2.1217	.21230 3.609
1.	1.6707 4.887	22.173 27.60	.10968 32.48	186.60 457.6	1769.5 809.7	1763.9 1249.7	168.70 .33727	.39126 .27505	.61958 .89208	.37518 .14455	.37505 .18752	.30995 .94820	.58157 2.2471	.22485 5.525
2.	1.6732 5.977	33.342 57.68	.21495 63.66	187.08 532.7	1737.2 869.9	1689.7 1240.2	148.92 .32371	.28548 .27550	.98180 .96695	.33664 .16138	.37550 .18775	.33368 .95489	.57564 2.1567	.21581 14.034
3.	1.6962 6.845	42.176 94.40	.34184 101.24	188.07 597.3	1710.2 921.5	1620.0 1228.0	140.66 .26739	.23599 .27642	.68517 .96419	.30657 .18461	.37642 .18821	.31360 .96077	.56801 1.7815	.17826 22.297
4.	1.7348 7.055	49.153 131.25	.46697 138.30	189.49 651.4	1687.7 965.2	1554.5 1215.4	142.11 .38399	.24146 .27776	.65896 .95983	.29951 .17446	.37776 .18888	.32076 .96571	.56009 2.5583	.25599 22.821
5.	1.7850 7.453	54.653 165.08	.58257 172.54	191.25 695.9	1668.9 1002.0	1492.8 1204.0	150.90 .39660	.27414 .27941	.54372 .94062	.30870 .18877	.37941 .18971	.34908 .96973	.55297 2.6424	.26440 25.126
6.	1.8439 7.779	58.981 194.64	.68345 202.42	193.29 732.0	1653.4 1032.5	1434.7 1195.1	164.77 .43977	.33398 .28132	.57438 .94573	.32040 .19817	.38132 .19066	.39226 .97294	.54743 2.9300	.29318 24.512
7.	1.9083 8.097	60.778 219.55	.76864 227.64	195.50 761.0	1640.4 1057.3	1380.2 1189.6	181.76 .45948	.40236 .28340	.53457 .93909	.35456 .21624	.38340 .19170	.44474 .97546	.54395 3.0613	.30632 25.309
8.	1.9724 8.538	61.095 236.75	.82820 245.28	197.72 784.7	1629.6 1077.0	1329.1 1187.7	199.90 .47674	.47361 .28547	.61966 .95328	.37272 .23989	.38547 .19274	.50073 .97748	.54276 3.1763	.31783 23.607
9.	2.0353 8.753	61.396 247.63	.86566 256.38	199.88 805.1	1620.5 1092.2	1281.3 1189.4	217.40 .49006	.51608 .28751	.54067 .94011	.37814 .28133	.38751 .19375	.55493 .97924	.54382 3.2650	.32670 25.187
10.	2.0968 9.252	61.683 254.75	.89140 264.00	202.01 823.1	1612.8 1103.4	1236.7 1194.4	233.38 .48774	.56566 .28950	.58922 .93561	.38314 .31683	.38950 .19475	.60475 .98085	.54695 3.2496	.32516 24.216
50.	3.5861 17.554	60.772 271.64	.97646 289.19	253.57 1147.6	1298.9 856.1	821.0 1707.1	321.37 .49168	.71570 .33787	.55135 .76617	.41901 .52247	.43787 .21893	.90246 .98251	.81689 3.2758	.32779 24.973
90.	3.9150 19.380	60.630 265.35	.96138 284.73	264.97 972.5	1172.6 885.9	912.6 1874.3	322.64 .50811	.72165 .34857	.55213 .82469	.45783 .51712	.44857 .22428	.89853 .93538	.84304 3.3853	.33874 24.349
130.	3.9807 19.745	60.601 259.01	.94121 278.76	267.25 778.3	1224.3 939.7	952.4 1920.5	322.89 .50417	.71845 .35070	.51159 .84431	.44306 .52170	.45070 .22535	.87177 .91310	.85027 3.3590	.33611 24.879
170.	3.9127 19.413	59.164 251.90	.91608 271.31	264.91 756.5	1264.3 954.8	953.2 1897.3	314.28 .49824	.70916 .34851	.53654 .84784	.45926 .49966	.44851 .22425	.84717 .91594	.84663 3.3195	.33216 24.467

PSE=S,PSA=A,PP6=6,PP8=8,PP1=1,PMT=M,POG=O



7.2 The Basic Mode (BASC)
(table 5 and figs. 47, 48, 49)

Timber production is about 0.9 of the maximum. The wildlife indices are scattered, but most are still rather low. Ugliness decreases, visual contrast improves, and sediment increases by a small amount.

Table 5.--Basic mode (BASC 25/10). Data for the control of timber sales and information about the volumes of timber removed, the distribution of habitats, the indices for some benefits, number of openings per square mile, and the distribution of opening sizes. For definitions see appendix B.

Figure 47.--Basic mode (BASC 25/10). The distribution of seedlings (S), saplings (A), 6-inch poles (6), 8-inch poles (8), 10-inch poles (1), mature timber (M), and old growth (O). Note the difference in scales which was necessary to illustrate the changes.

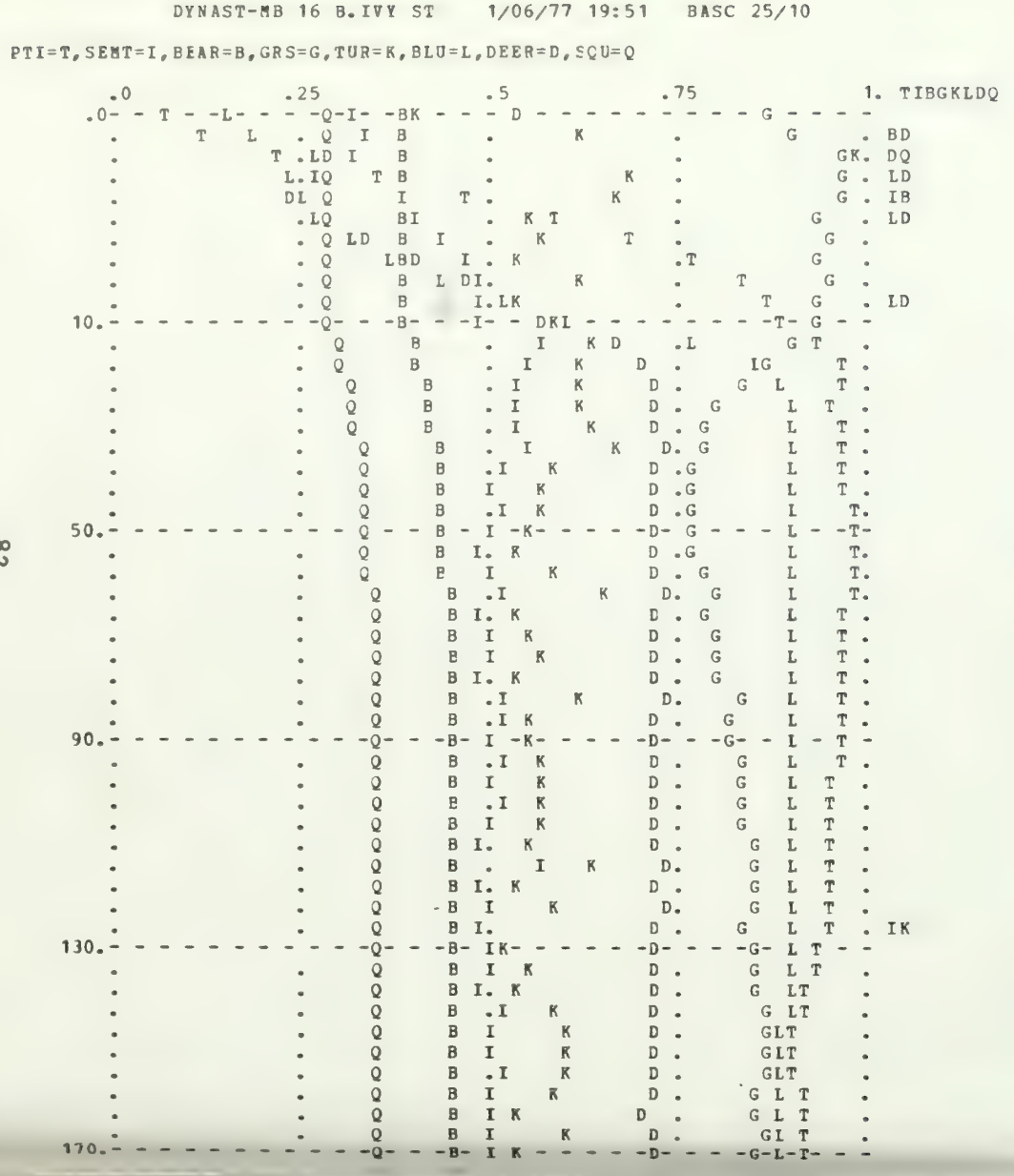


Figure 48.--Basic mode (BASC 25/10). Changes in the indices for potential timber (T), sediment (I), bear (B), grouse (G), turkey (K), bluebird group (L), deer (D), and squirrels (Q).

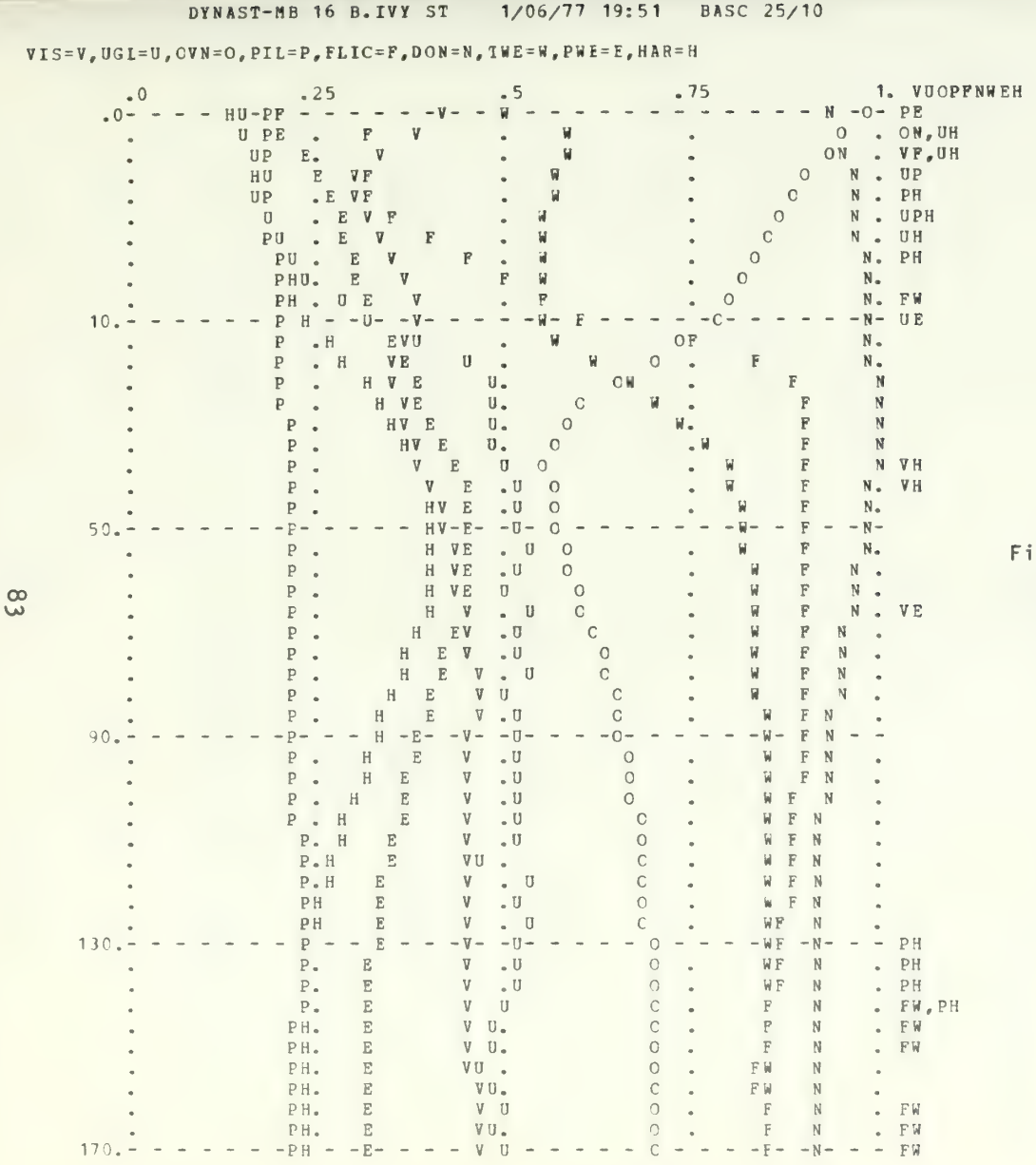


Figure 49.--Basic mode (BASC 25/10). Changes in the indices for visual variety (V), ugliness (U), ovenbird group (O), pileated woodpecker (P), flicker (F), downy (N), towhee group (W), pewee group (E), and hairy woodpecker (H).

TIME	OGS VOG	MTS VMT	PTI VT	OG MT	P1 P8	P6 SA	SE SEMT	DEER SQU	TUR GRS	VIS UGL	BEAR PIL	FLIC DON	TWE NOP	OPM OPS
E+00	E+00 E+03	E+00 E+03	E+00 E+03	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00
.0	.0000	13.691	.09525	185.0	1808.0	1843.0	200.00	.52237	.74622	.41442	.37355	.42775	.58424	.09551
	.000	28.21	28.21	379.7	740.0	1254.0	.14326	.27355	.90959	.20735	.18677	.9420	.9545	7.151
1.	.0000	24.963	.14355	188.7	1769.5	1763.9	170.75	.39378	.92800	.38033	.37701	.38654	.58166	.10654
	.000	42.52	42.52	457.3	809.7	1249.9	.15982	.27701	.92956	.17923	.18850	.9481	1.0648	9.547
2.	.0000	33.867	.24136	194.5	1737.2	1689.7	152.43	.29242	.86608	.34786	.38244	.34368	.57606	.09245
	.000	71.48	71.48	525.0	869.9	1240.9	.13868	.28244	.99738	.19440	.19122	.9537	.9240	18.314
3.	.0000	40.887	.35154	201.9	1710.2	1620.1	144.33	.25333	.74717	.32013	.38944	.32411	.56887	.11608
	.000	104.11	104.11	582.3	921.5	1229.4	.17412	.28944	.97453	.19150	.19472	.9584	1.1601	21.057
4.	.0000	46.411	.45847	210.7	1687.7	1554.6	144.55	.25729	.85443	.31275	.39766	.32786	.56133	.16731
	.000	135.78	135.78	629.6	965.3	1217.4	.25097	.29766	.99241	.17918	.19883	.9623	1.6721	18.911
5.	.0000	47.511	.55160	220.3	1668.9	1492.9	150.91	.28145	.74373	.31957	.40665	.34917	.55437	.17913
	.000	163.37	163.37	668.4	1002.0	1206.2	.26869	.30665	.97395	.19377	.20333	.9654	1.7901	21.125
6.	.0000	47.940	.61349	230.0	1653.4	1435.0	160.54	.32413	.78150	.33358	.41575	.38015	.54861	.20555
	.000	181.69	181.69	701.3	1032.5	1197.0	.30832	.31575	.98025	.19970	.20788	.9681	2.0542	20.370
7.	.0000	48.347	.65362	239.8	1640.5	1380.5	171.19	.36846	.74387	.34969	.42494	.41427	.54429	.21025
	.000	193.58	193.58	730.4	1057.3	1190.1	.31537	.32494	.97398	.21482	.21247	.9707	2.1012	21.123
8.	.0000	48.737	.68077	249.7	1629.6	1329.3	181.66	.41743	.83396	.36541	.43420	.44808	.54143	.23841
	.000	201.62	201.62	756.8	1077.0	1185.5	.35762	.33420	.98899	.21339	.21710	.9731	2.3826	19.321
9.	.0000	49.110	.70012	259.6	1620.5	1281.4	191.39	.45551	.75235	.37970	.44353	.47990	.53992	.22524
	.000	207.35	207.35	781.3	1092.2	1183.1	.33787	.34353	.97539	.23537	.22177	.9755	2.2510	20.953
10.	.0000	49.469	.71476	269.6	1612.8	1236.6	200.16	.48399	.80294	.38141	.45294	.50904	.53963	.24076
	.000	211.69	211.69	804.5	1103.4	1182.7	.36114	.35294	.97070	.24709	.22647	.9779	2.4061	19.941
50.	3.3649	49.460	.83374	686.4	1260.5	714.9	260.23	.64967	.79088	.54364	.80732	.71373	.68770	.32958
	14.937	231.99	246.93	1277.4	790.6	1419.4	.49437	.70732	.73351	.35081	.41464	.9968	3.2938	20.182
90.	7.2874	47.992	.87243	900.6	1028.5	761.5	274.95	.67551	.77650	.70612	.84081	.75975	.78102	.33505
	36.026	222.36	258.38	1128.5	746.7	1568.6	.50258	.74081	.77045	.37035	.48162	.9372	3.3484	18.896
130.	8.7397	47.448	.86160	979.9	1035.7	809.6	280.40	.68211	.70571	.76857	.85321	.77680	.80718	.32872
	43.952	211.23	255.18	865.1	793.7	1644.9	.49308	.75321	.79791	.38740	.50641	.8944	3.2851	19.248
170.	9.2775	47.247	.85039	1009.3	1081.0	833.5	282.42	.68636	.69704	.74991	.85780	.78312	.81246	.33034
	46.901	204.96	251.86	698.8	825.4	1678.7	.49551	.75780	.81521	.38812	.51560	.8566	3.3013	18.887

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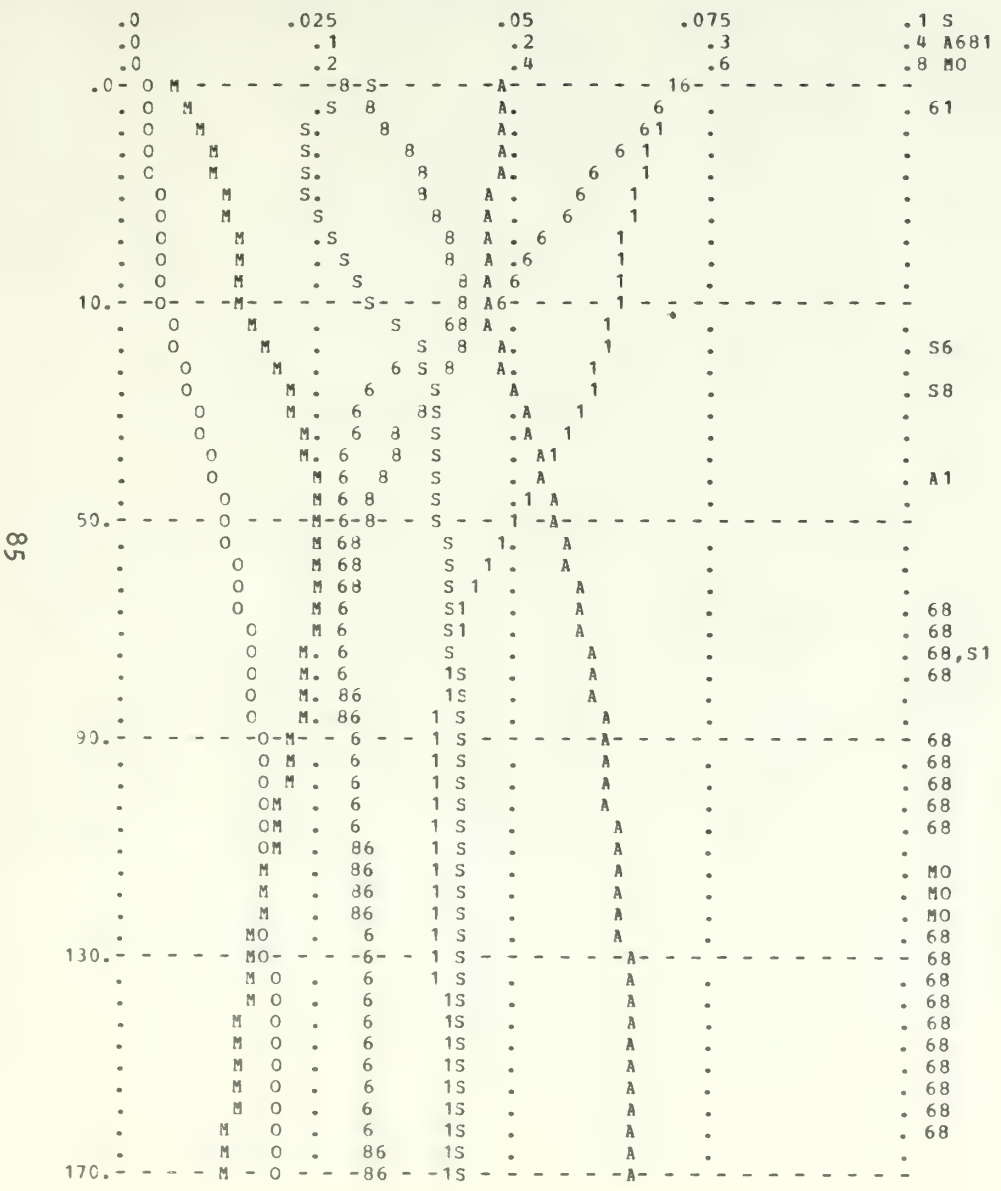


7.3 The Moderate Mode (MODR)
(table 6 and figs. 50, 51, 52)

Timber production is reduced to about 0.85 of the maximum, but the benefit indices are clustered at fairly high levels, between 0.5 and 0.9, and no impact is at an unacceptable value. Furthermore, as the distribution of habitats moves toward a steady state, about 20 percent of the harvested volume of timber is from old-growth habitats, which produce a high volume per acre at harvest. The logs should have higher quality than those removed from the faster modes of management, since large diameter is an important variable affecting the quality of hardwood logs. The slower modes of management increase the harvest from the old-growth habitat, thus improving the quality of the harvest.

Table 6.--Moderate mode (MODR 20/10). Data for the control of timber sales and information about the volumes of timber removed, the distribution of habitats, the indices for some benefits, number of openings per square mile, and the distribution of opening sizes. For definitions see appendix B.

Figure 50.--Moderate mode (MODR 20/10). The distribution of seedlings (S), saplings (A), 6-inch poles (6), 8-inch poles (8), 10-inch poles (1), mature timber (M), and old growth (0). Note the difference in scales which was necessary to illustrate the changes.

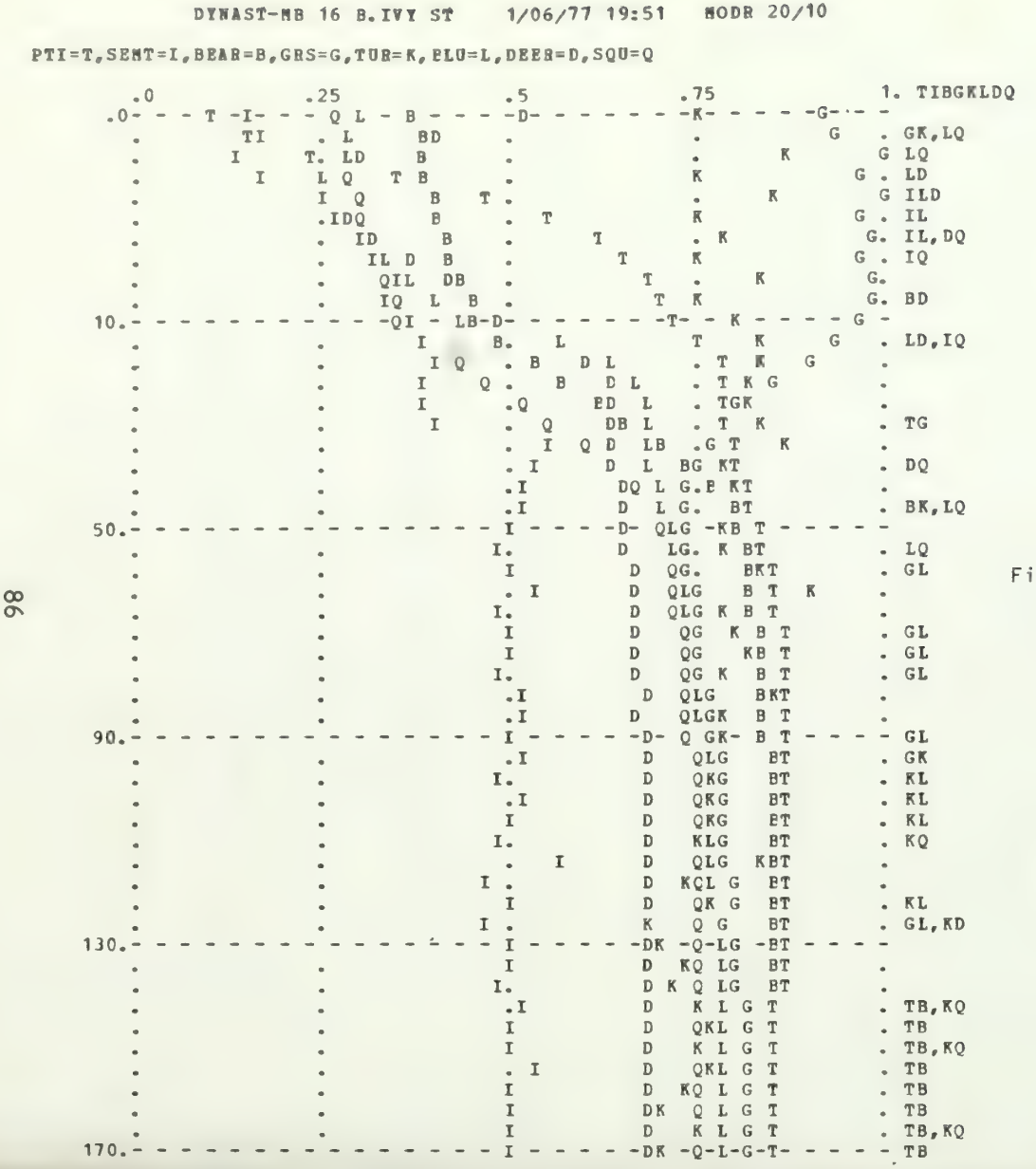


Figure 51.--Moderate mode (MODR 20/10). Changes in the indices for potential timber (T), sediment (I), bear (B), grouse (G), turkey (K), bluebird group (L), deer (D), and squirrels (Q).

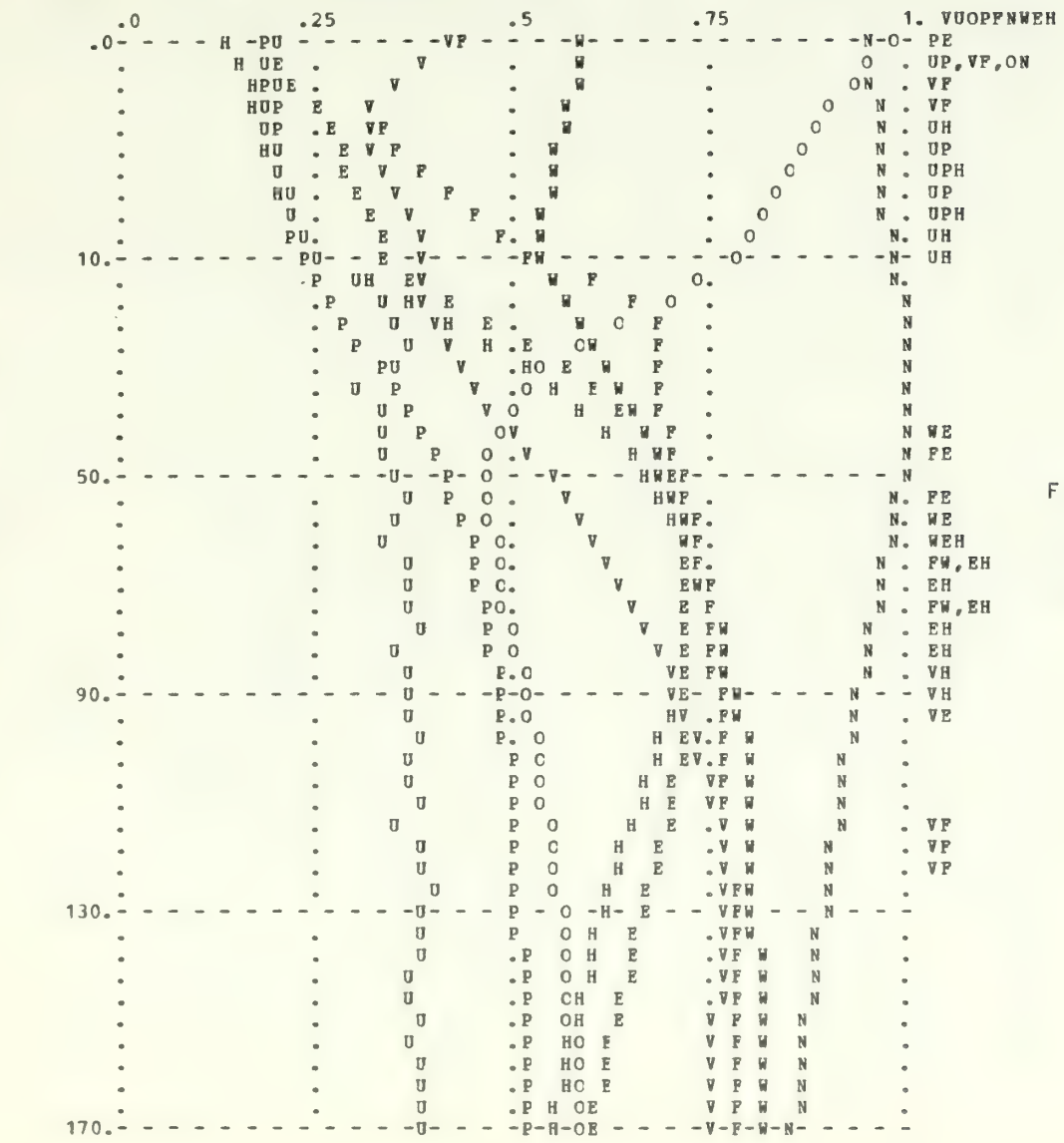


Figure 52.--Moderate mode (MODR 20/10). Changes in the indices for visual variety (V), ugliness (U), ovenbird group (O), pileated woodpecker (P), flicker (F), downy (N), towhee group (W), pewee group (E), and hairy woodpecker (H).

DYNAST-MB 16 B.IVY ST 1/06/77 19:51 SLOW 10/5

TIME	QGS VOG	MTS VMT	PTI VT	OG MT	P1 P8	P6 SA	SE SEMT	DEER SOU	TUR GRS	VIS UGL	BEAR PIL	FLIC DON	TWE NOP	OPM OPS
E+00	E+00 E+03	E+00 E+03	E+00 E+03	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00
.0	.000	19.380	.13838	185.0	1808.0	1843.0	200.00	.51455	.9173	.41488	.37355	.46148	.58424	.09555
	.000	40.98	40.98	385.4	740.0	1254.0	.14332	.27355	.93440	.22271	.18677	.9429	.9549	10.128
1.	.000	27.832	.19870	193.6	1769.5	1763.9	173.77	.40809	.9185	.38847	.38164	.39329	.58180	.14615
	.000	58.85	58.85	454.8	809.7	1250.1	.21923	.28164	.92803	.17781	.19082	.9478	1.4606	9.363
2.	.000	33.744	.29419	205.2	1737.2	1689.8	157.97	.33179	.9758	.36549	.39249	.35944	.57670	.17587
	.000	87.13	87.13	513.4	869.9	1241.9	.26380	.29249	.94482	.16662	.19625	.9519	1.7576	11.378
3.	.000	34.316	.38147	218.1	1710.2	1620.1	150.77	.29941	.9990	.34158	.40460	.34254	.57024	.23210
	.000	112.98	112.98	563.1	921.5	1231.6	.34815	.30460	.94217	.15024	.20230	.9554	2.3195	11.061
4.	.000	34.859	.43916	231.2	1687.7	1554.7	148.89	.29401	.9957	.33063	.41691	.33113	.56338	.32837
	.000	130.07	130.07	607.0	965.3	1220.6	.49256	.31691	.92429	.12548	.20845	.9588	3.2817	8.914
5.	.000	35.375	.47824	244.5	1668.9	1493.2	149.90	.29533	1.0000	.32651	.42940	.34638	.55667	.28412
	.000	141.64	141.64	646.9	1002.0	1209.9	.42618	.32940	.94273	.14063	.21470	.9621	2.8394	11.128
6.	.000	35.869	.50609	258.1	1653.4	1435.3	152.42	.30802	1.0000	.32582	.44208	.35674	.55038	.32005
	.000	149.89	149.89	683.8	1032.5	1199.9	.48008	.34208	.93643	.13435	.22104	.9654	3.1985	10.372
7.	.000	36.342	.52713	271.8	1640.5	1380.9	155.65	.32160	1.0000	.32669	.45493	.36924	.54465	.30859
	.000	156.12	156.12	718.6	1057.4	1190.7	.46288	.35493	.94270	.14163	.22746	.9688	3.0839	11.124
8.	.000	36.798	.54402	285.6	1629.7	1329.7	159.16	.34076	.9661	.32815	.46795	.37615	.53953	.37736
	.000	161.12	161.12	751.6	1077.1	1182.5	.56603	.36795	.92769	.12684	.23397	.9723	3.7712	9.322
9.	.000	37.237	.55831	299.7	1620.6	1281.6	162.70	.35416	1.0000	.32971	.48112	.39622	.53501	.32748
	.000	165.35	165.35	783.2	1092.3	1175.3	.49122	.38112	.94129	.14396	.24056	.9758	3.2728	10.954
10.	.000	37.661	.57096	313.9	1612.8	1236.4	166.17	.37192	.9971	.33113	.49445	.40906	.53108	.36665
	.000	169.10	169.10	813.6	1103.5	1169.0	.54998	.39445	.92037	.13636	.24723	.9794	3.6642	9.943
50.	.000	37.540	.61161	960.0	1224.5	613.4	187.70	.46785	1.0000	.35707	.85009	.48692	.50801	.33453
	.000	181.14	181.14	1568.6	728.9	1132.1	.50179	.75009	.62177	.16554	.50018	1.0000	3.3432	11.216
90.	6.051	35.883	.68384	1472.0	876.7	580.0	206.74	.53589	.9261	.59181	.93014	.54479	.53569	.45427
	29.413	173.12	202.53	1513.2	590.2	1176.4	.65427	.86027	.56571	.15316	.66027	.9737	4.5398	9.877
130.	9.350	34.797	.71658	1734.5	803.4	615.4	219.24	.57407	.8054	.78683	.97119	.58442	.58805	.49916
	47.155	165.07	212.23	1179.6	602.8	1260.1	.69916	.94237	.61757	.15205	.74237	.9100	4.9885	9.922
170.	11.035	34.242	.73057	1868.5	830.2	649.4	225.62	.59522	.6819	.90461	.92806	.59639	.62522	.53967
	56.303	160.07	216.37	884.2	637.5	1319.5	.73967	.92071	.65549	.14055	.78428	.8361	5.3933	9.398

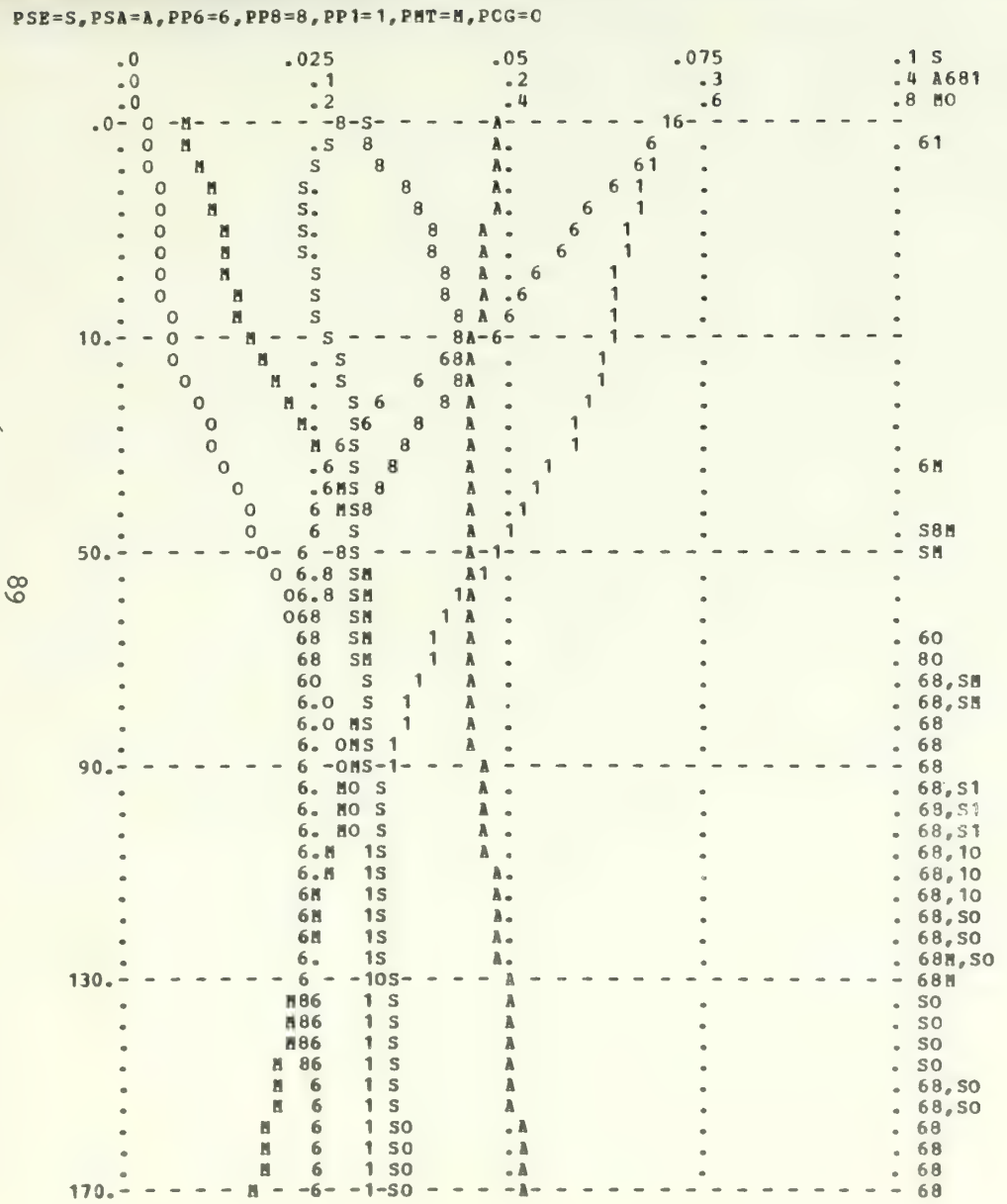


Figure 53.--Slow mode (SLOW 10/5). The distribution of seedlings (S), saplings (A), 6-inch poles (6), 8-inch poles (8), 10-inch poles (1), mature timber (M), and old growth (O). Note the difference in scales which was necessary to illustrate the changes.

7.4 The Slow Mode (SLOW)
(table 7 and figs. 53, 54, 55)

Timber production is further reduced to about 0.7 of the maximum. The indices are dispersed, with squirrel and bear high and two of the songbirds below 0.5. From the esthetic standpoint, this is a desirable mode; ugliness is low and visual contrast is high. Sedimentation has increased because of the reduced size of openings, the increased number of openings per square mile, and the associated increase in the miles of roads and skid trails.

Table 7.--Slow mode (SLOW 10/5). Data for the control of timber sales and information about the volumes of timber removed, the distribution of habitats, the indices for some benefits, number of openings per square mile, and the distribution of opening sizes. For definitions see appendix B.

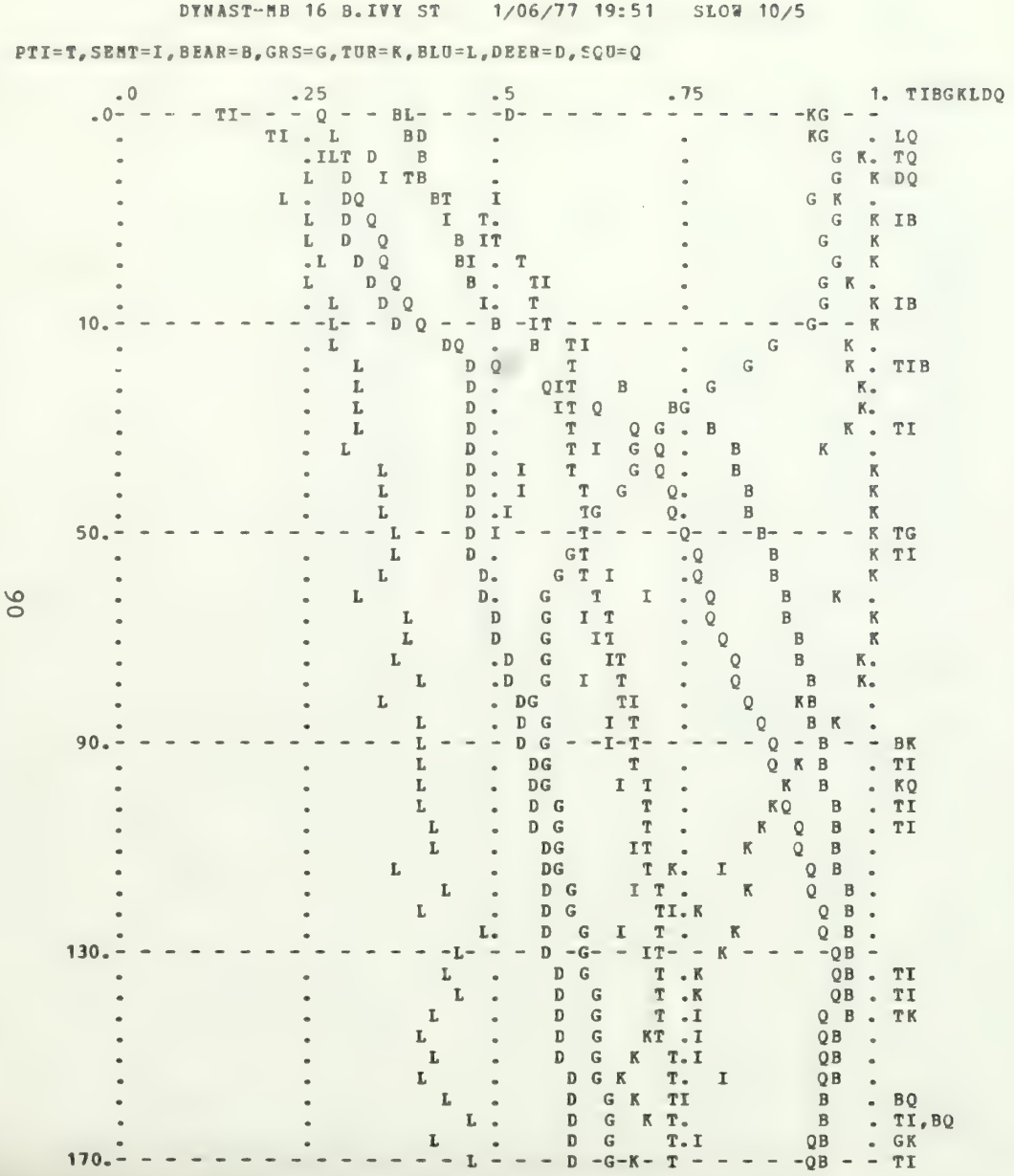


Figure 54.--Slow mode (SLOW 10/5). Changes in the indices for potential timber (T), sediment (I), bear (B), grouse (G), turkey (K), bluebird group (L), deer (D), and squirrels (Q).

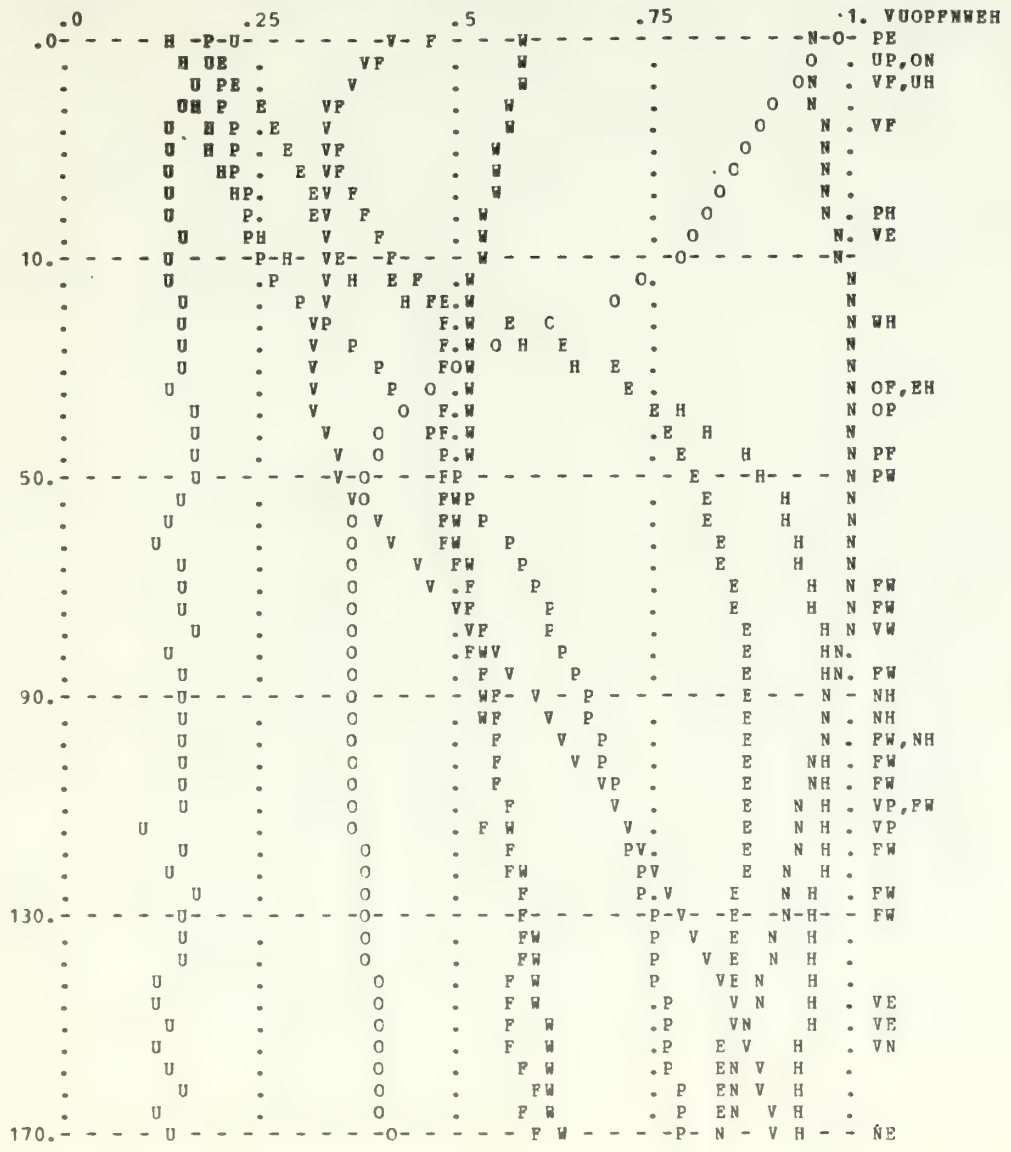
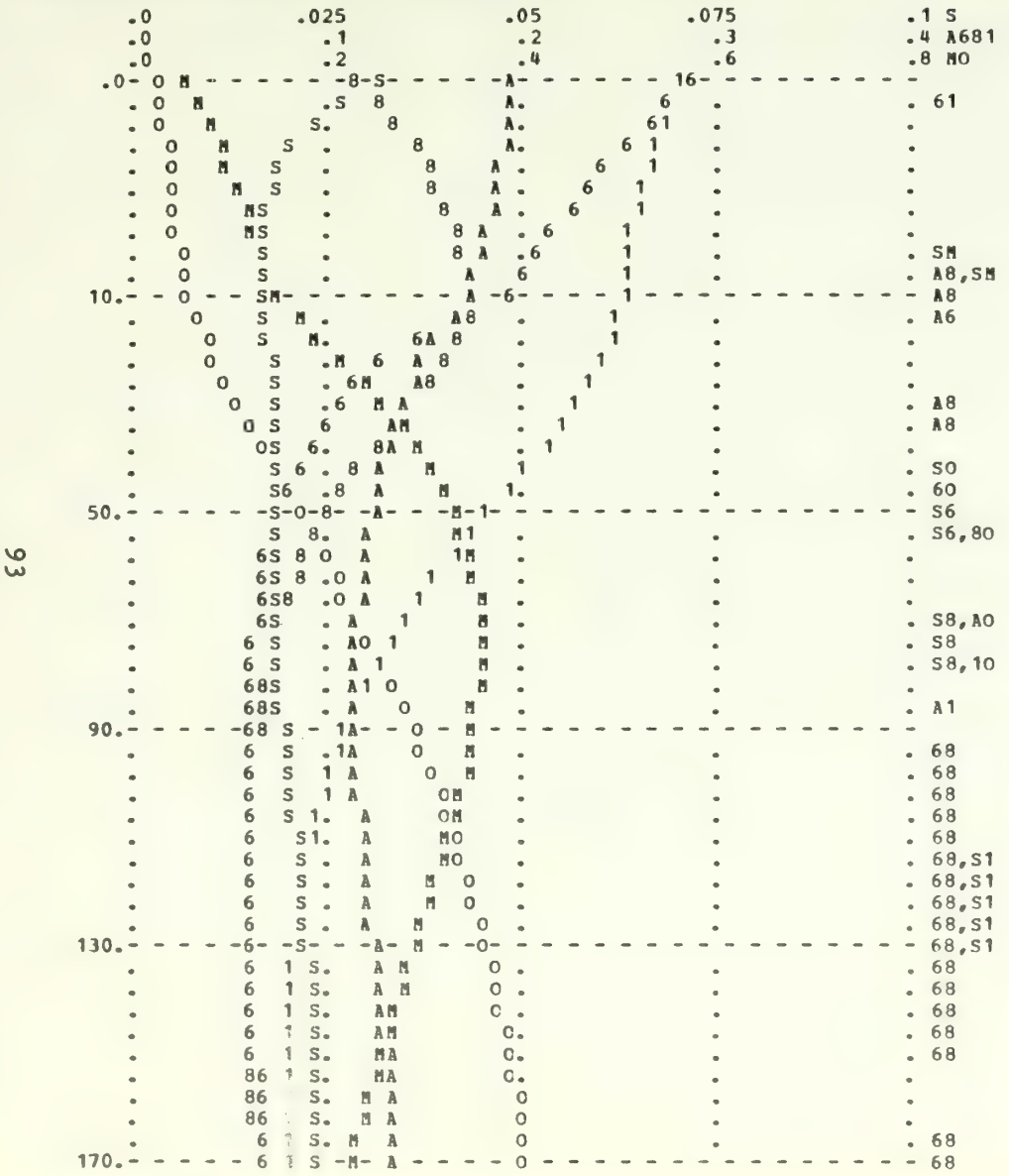


Figure 55.--Slow mode (SLOW 10/5). Changes in the indices for visual variety (V), ugliness (U), ovenbird group (O), pileated woodpecker (P), flicker (F), downy (N), towhee group (W), pewee group (E), and hairy woodpecker (H).

TIME	OGS VOG	MTS VMT	PTI VT	OG MT	P1 P8	P6 SA	SE SEMT	DEER SQU	TUR GRS	VIS UGL	BEAR PIL	FLIC DON	TWE NOP	OPM OPS
E+00	E+00 E+03	E+00 E+03	E+00 E+03	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00
.0	.000	8.262	.06258	185.0	1808.0	1843.0	200.00	.52539	.48059	.41338	.37355	.25367	.54097	.0966
	.000	18.53	18.53	374.3	740.0	1254.0	.1449	.2735	.87099	.17434	.18677	.9412	.965	4.2593
1.	.000	13.608	.09344	193.0	1769.5	1763.9	167.59	.38606	.54983	.37461	.38109	.25230	.57007	.1245
	.000	27.67	27.67	450.9	809.7	1249.7	.1867	.2811	.88005	.14501	.19054	.9471	1.244	4.8031
2.	.000	18.147	.14954	205.0	1737.2	1689.7	144.08	.27579	.62646	.33188	.39230	.25027	.57532	.1746
	.000	44.29	44.29	518.6	869.9	1239.7	.2620	.2923	.89016	.12756	.19615	.9527	1.745	5.4095
3.	.000	19.478	.20991	219.8	1710.2	1620.0	128.40	.20223	.63155	.28858	.40616	.21276	.56680	.2483
	.000	62.17	62.17	578.4	921.5	1226.1	.3724	.3062	.88859	.10528	.20308	.9578	2.481	5.3155
4.	.000	19.855	.25255	235.0	1687.7	1554.3	118.48	.18524	.56723	.25288	.42047	.16497	.53865	.3383
	.000	74.80	74.80	633.2	965.2	1210.3	.5074	.3205	.87787	.08235	.21024	.9629	3.381	4.6723
5.	.000	20.218	.28065	250.6	1668.9	1492.4	112.25	.17550	.63363	.22873	.43506	.19112	.54631	.3278
	.000	83.12	83.12	684.7	1002.0	1193.3	.4917	.3351	.88894	.08359	.21753	.9680	3.276	5.3363
6.	.000	20.570	.30010	266.4	1653.4	1434.0	108.39	.16946	.61097	.21201	.44991	.17551	.53540	.3646
	.000	88.88	88.88	733.8	1032.4	1175.9	.5469	.3499	.88516	.07546	.22495	.9732	3.644	5.1097
7.	.000	20.912	.31439	282.5	1640.4	1378.7	106.09	.16587	.63355	.20002	.45967	.18442	.52446	.3644
	.000	93.11	93.11	780.9	1057.1	1158.4	.5466	.3650	.88892	.07526	.23251	.9786	3.642	5.3355
8.	.000	21.246	.32557	298.9	1629.6	1326.5	104.85	.16394	.57951	.19105	.46789	.15816	.50313	.4182
	.000	96.42	96.42	826.5	1076.8	1141.1	.6182	.3804	.87992	.06503	.24018	.9840	4.180	4.7951
9.	.000	21.570	.33487	315.5	1620.5	1277.2	104.34	.16314	.62847	.18402	.47632	.18254	.50308	.3890
	.000	99.18	99.18	870.7	1091.8	1124.2	.5835	.3960	.88752	.07125	.24798	.9895	3.887	5.2847
10.	.000	21.888	.34301	332.4	1612.7	1230.5	104.35	.16314	.59813	.17825	.48496	.16950	.49190	.4212
	.000	101.59	101.59	913.9	1102.6	1107.8	.6212	.4118	.86957	.06531	.25589	.9950	4.209	4.9813
50.	.000	22.954	.39156	1095.7	1167.5	482.9	114.77	.17944	.63632	.17451	.61910	.20796	.29666	.4273
	.000	115.97	115.97	2107.3	641.8	794.2	.6273	.7713	.40469	.07311	.54261	1.0000	4.270	5.3632
90.	3.354	22.316	.42951	1833.9	695.4	375.9	124.21	.19421	.56977	.22767	.65779	.18630	.24790	.7447
	13.646	113.56	127.21	2234.1	412.0	728.5	.8723	.9735	.25272	.01339	.77345	1.0000	7.442	4.6977
130.	8.051	21.046	.47766	2313.2	535.0	384.8	143.03	.27087	.44694	.25180	.73311	.18498	.27219	1.2596
	35.559	105.91	141.47	1853.2	379.9	794.8	1.0000	1.0000	.26218	.00125	.86167	.9734	12.588	4.1635
170.	10.841	20.292	.50625	2598.0	530.4	422.8	154.21	.32329	.32687	.40454	.75240	.17266	.30333	1.5274
	49.285	100.65	149.93	1415.8	409.0	873.6	1.0000	.9365	.31139	.00130	.90309	.9043	15.265	3.7588

PSE=S,PSA=A,PP6=6,PP8=8,PP1=1,PMT=M,POG=O



7.5 The Very Slow Mode (VSLO)
(table 8 and figs. 56, 57, 58)

Timber production is only about 0.5 of the maximum. The other indices for benefits and impacts are widely dispersed. Compared with the faster modes, the indices for the bluebird group, deer, grouse, turkey, flicker, ovenbird group, and towhee group are down. Ugliness is very low, but so is visual contrast. Sediment flow is relatively high and increases to unacceptable levels within 100 years.

Table 8.--Very slow mode (VSLO 5/1). Data for the control of timber sales and information about the volumes of timber removed, the distribution of habitats, the indices for some benefits, number of openings per square mile, and the distribution of opening sizes. For definitions see appendix B.

Figure 56.--Very slow mode (VSLO 5/1). The distribution of seedlings (S), saplings (A), 6-inch poles (6), 8-inch poles (8), 10-inch poles (1), mature timber (M), and old growth (O). Note the difference in scales which was necessary to illustrate the changes.

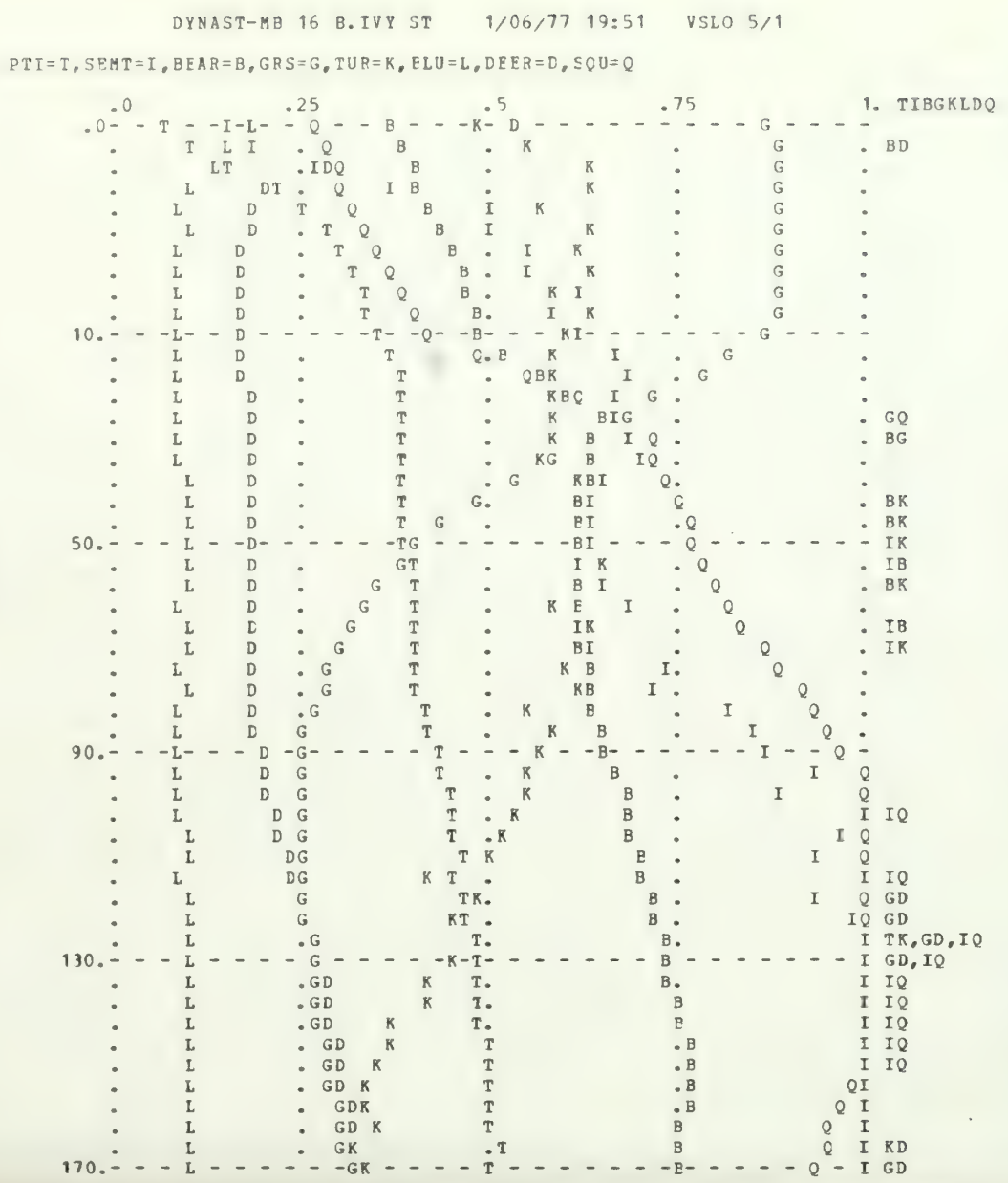


Figure 57.--Very slow mode (VSLO 5/1). Changes in the indices for potential timber (T), sediment (I), bear (B), grouse (G), turkey (K), bluebird group (L), deer (D), and squirrels (Q).

```
DYNAST-MB 16 B.IVY ST    1/06/77 19:51   VSLO 5/1

VIS=V,UGI=U,OVN=O,PIL=P,FLIC=F,DON=N,TWE=W,PWE=E,HAR=H

```

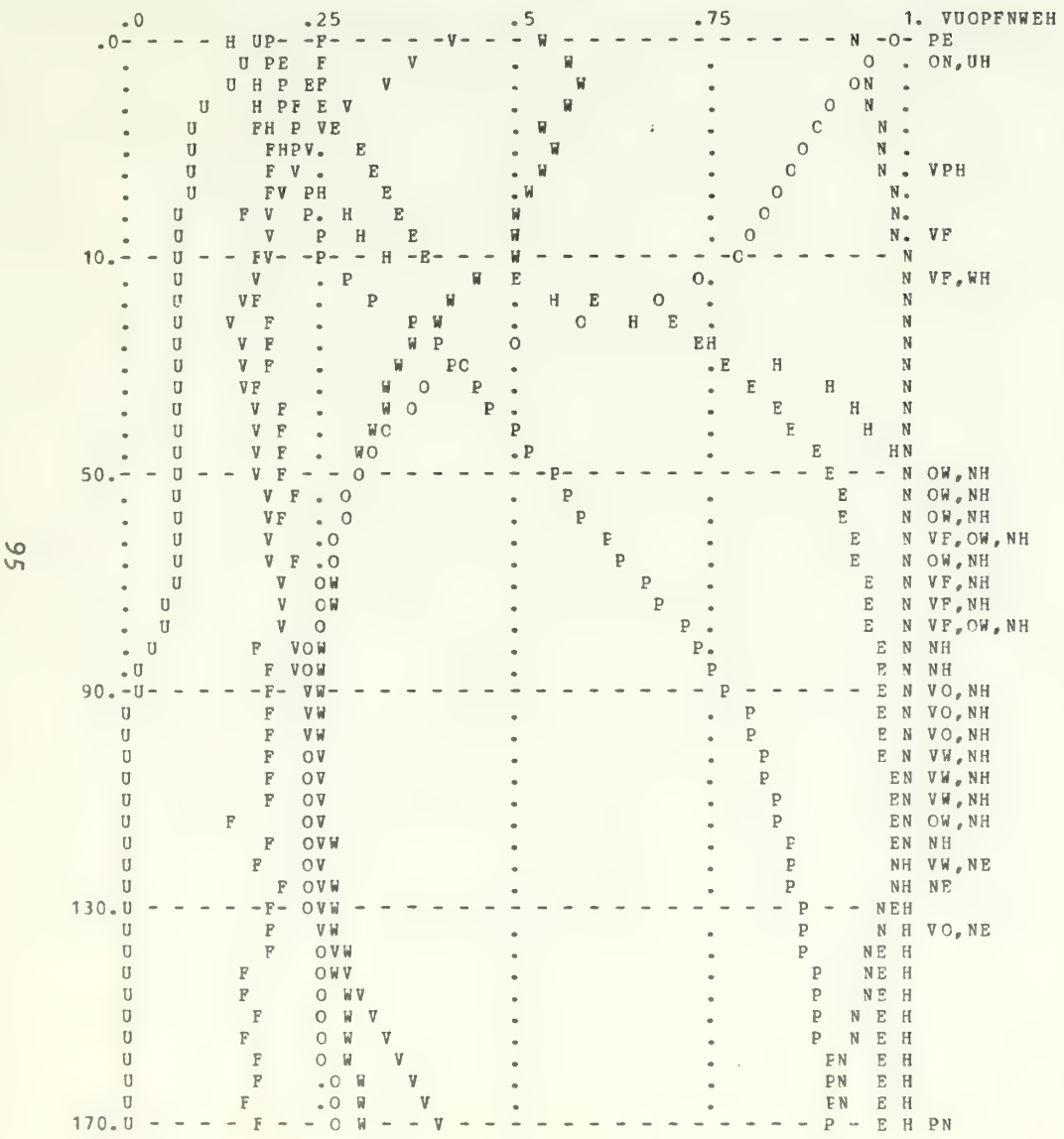
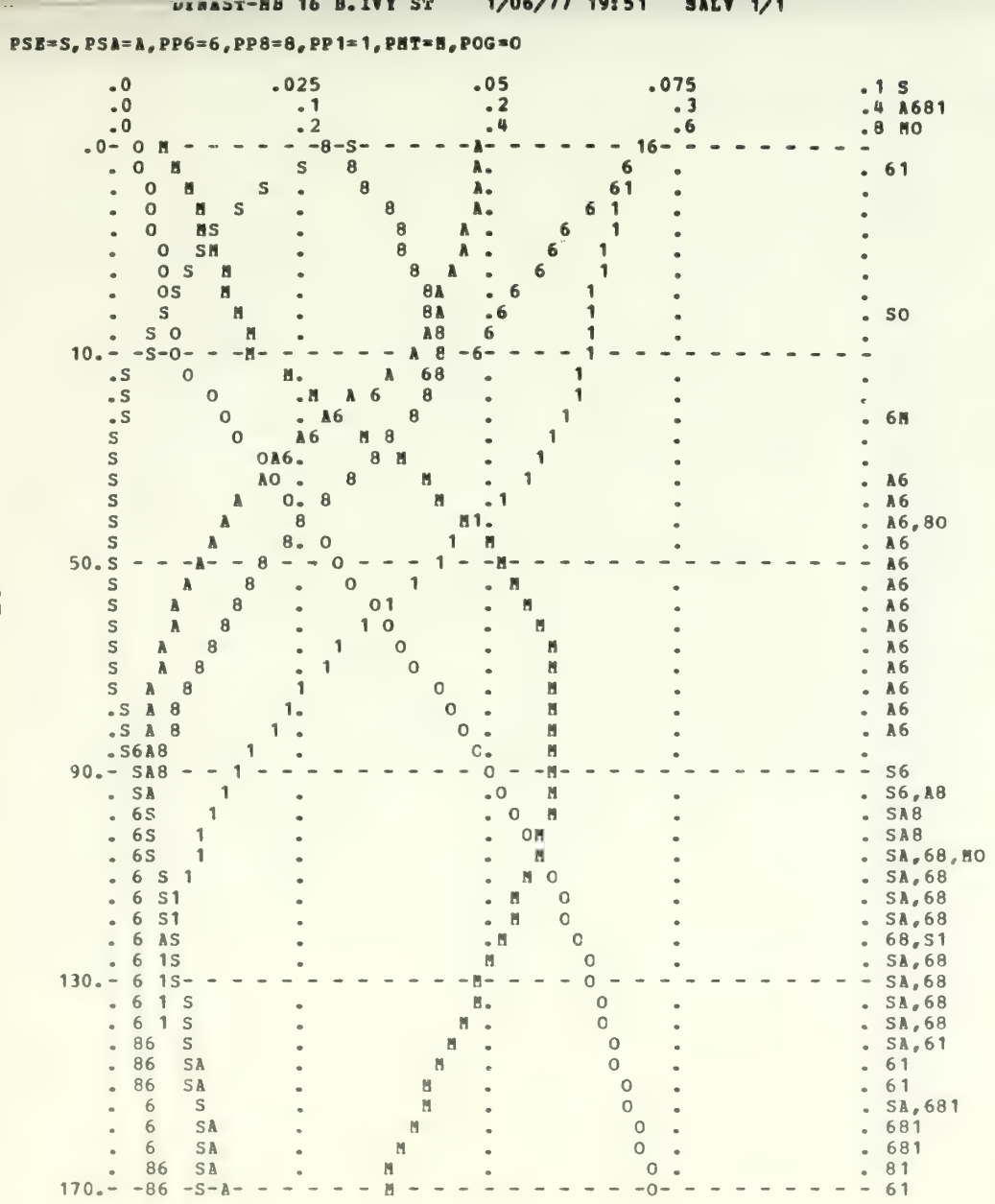

.0 .25 .5 .75 1. VUOPFNWEH
.0- - - - H UP- -F- - - - -V- - - W - - - - - - - - - - - N -O- PE
. U PE F V . W . O . ON,UH
. U H P EP V . W . ON .
. U H PF E V . W . O N .
. U PH P VE . W . C N .
. U FHPV. E . W . O N .
. U F V . E . W . C N . VPH
. U FV PH E .W . O N.
. U F V P. H E W . O N.
. U V P H E W . O N. VF
10.- - U - - FV- -P- - H -E- - - W - - - - - - - -C- - - - - - N
. U V . P W E O. N VF,WH
. U VF . P W . H E O . N
. U V F . P W . O H E . N
. U V F . W P O EH N
. U V F . W PC .E H N
. U VF . W O P . E H N
. U V F . W O P . E H N
. U V F . WC P . E H N
. U V F . WO .P . E HN
50.- - U - - V F - - O - - - - - - - -P- - - - - - - - - - E - - N OW,NH
. U V F . O . P . E N OW,NH
. U VF . O . P . E N OW,NH
. U V .O . P . E N VF,OW,NH
. U V F .O . P . E N OW,NH
. U V OW . P . E N VF,NH
. U V OW . P . E N VF,NH
. U V O . P . E N VF,OW,NH
. U F VOW . P. E N NH
.U F VOW . P E N NH
90.-U- - - - -F- VW- - - - - - - - - - - - - - - - P - - - - - E N VO,NH
U F VW . . P E N VO,NH
U F VW . . P E N VO,NH
U F OV . . P E N VW,NH
U F OV . . P EN VW,NH
U F OV . . P EN VW,NH
U F OV . . P EN OW,NH
U F OVW . . P EN NH
U F OV . . P NH VW,NE
U F OVW . . P NH NE
130.U - - - - -F- OVW - - - - - - - - - - - - - - - - - - P - - NEH
U F VW . . P N H VO,NE
U F OVW . . P NE H
U F OWV . . P NE H
U F O WV . . P NE H
U F O W V . . P N E H
U F O W V . . P N E H
U F O W V . . PN E H
U F .O W V . . PN E H
U F .O W V . . PN E H
170.U - - - - F - - O W - - V - - - - - - - - - - - - - - - - P - E H PN

Figure 58.--Very slow mode (VSLO 5/1). Changes in the indices for visual variety (V), ugliness (U), ovenbird group (O), pileated woodpecker (P), flicker (F), downy (N), towhee group (W), pewee group (E), and hairy woodpecker (H).

TIME	OGS VOG	MTS VMT	PTI VT	OG MT	P1 P8	P6 SA	SE SEMT	DEER SQU	TUR GRS	VIS UGL	BEAR PIL	FLIC DON	TWE NOP	OPM OPS
E+00	E+00 E+03	E+00 E+00	E+00 E+03	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E-03	E+00 E+00	E-03 E+00	E+00 E+00	E+00 E+00
.0	.000 .000	.31748 501.3	.00169 .501	185.0 366.3	1808.0 740.0	1843.0 1254.0	200.00 .1353	.52539 .2735	.01424 .80260	.41334 8.091	.37355 .18677	24.708 .9399	.09494 .902	.0902 .1562
1.	.000 .000	.44779 736.7	.00249 .737	207.0 433.8	1769.5 809.7	1763.9 1249.3	163.08 .1529	.36491 .2941	.01889 .80334	.36849 8.086	.39414 .19707	20.301 .9445	.10476 1.019	.1019 .2005
2.	.000 .000	.55361 1230.4	.00415 1.230	229.8 498.6	1737.2 869.9	1689.7 1238.1	133.10 .1284	.22427 .3155	.03474 .80596	.31421 11.875	.41554 .20777	17.031 .9496	.13960 .855	.0856 .3577
3.	.000 .000	.63948 1751.3	.00591 1.751	253.4 560.9	1710.2 921.5	1619.9 1221.7	108.77 .1328	.17006 .3377	.04588 .80766	.23690 12.449	.43770 .21885	14.545 .9551	.16010 .885	.0885 .4596
4.	.000 .000	.70909 2124.6	.00717 2.125	277.8 621.0	1687.7 965.2	1554.1 1201.5	89.04 .1648	.13922 .3606	.04539 .80756	.17211 9.953	.46062 .23031	12.049 .9610	.15524 1.098	.1098 .4539
5.	.000 .000	.76551 2642.2	.00892 2.642	303.0 679.3	1668.9 1002.0	1491.8 1178.3	73.06 .1329	.11422 .3842	.06587 .81098	.12077 11.984	.47369 .24212	10.859 .9671	.19513 .895	.0886 .6587
6.	.000 .000	.79972 2974.0	.01004 2.974	328.9 735.9	1653.4 1032.3	1432.8 1152.9	60.11 .1426	.09398 .4086	.06876 .81146	.09135 10.257	.48226 .25429	9.349 .9736	.19539 .950	.0951 .6876
7.	.000 .000	.82127 3298.0	.01114 3.298	355.6 790.9	1640.4 1057.0	1376.8 1126.0	49.61 .1332	.07757 .4336	.07976 .81329	.08842 9.854	.49038 .26679	8.737 .9801	.21128 .888	.0888 .7976
8.	.000 .000	.83148 3406.8	.01150 3.407	382.9 844.7	1629.6 1076.4	1323.5 1098.1	41.11 .1587	.06427 .4592	.07062 .81177	.08519 7.165	.49800 .27960	7.669 .9868	.18617 1.058	.1058 .7062
9.	.000 .000	.83148 3653.9	.01234 3.654	410.4 897.7	1620.4 1091.2	1272.8 1069.5	34.21 .1354	.05349 .4849	.08590 .81269	.08161 7.312	.50470 .29247	7.397 .9937	.20798 .902	.0903 .8590
10.	.000 .000	.83148 3670.4	.01239 3.670	437.8 950.4	1612.6 1101.8	1224.5 1040.6	28.61 .1491	.04473 .5107	.07952 .79934	.07765 5.634	.51045 .30534	6.620 1.0000	.18846 .993	.0994 .7952
50.	.000 .000	.83148 3882.5	.01311 3.882	1535.3 2646.6	1092.0 522.0	297.2 298.8	4.16 .1324	.00651 .8801	.09217 .15156	.07520 .956	.22267 .68009	4.128 1.0000	.04380 .882	.0982 .9217
90.	4.633 18.777	.83148 3843.0	.07638 22.620	2582.3 3000.3	435.3 156.0	87.4 115.3	19.49 .7256	.03047 1.0000	.09348 .04460	.07170 2.429	.10535 .90187	5.904 1.0000	.01708 5.252	.5256 .9348
130.	11.321 49.978	.82585 3876.4	.18184 53.855	3264.9 2514.1	166.8 84.3	89.3 220.7	55.96 1.0000	.08749 1.0000	.07752 .04554	.06233 .131	.21624 .95523	9.956 1.0000	.03164 13.070	1.3078 .8965
170.	15.294 69.514	.75011 3426.0	.24628 72.939	3670.3 1839.0	151.9 132.7	157.5 367.1	77.42 1.0000	.12105 .8641	.05508 .08033	.07415 .186	.30027 .98692	13.273 .9113	.05391 16.995	1.7005 .9241


DYNAST-RB 16 B.IVY SF 1/06/77 19:51 SALV 1/1
PSE=S,PSA=A,PP6=6,PP8=8,PP1=1,PMT=M,POG=O
.0 .025 .05 .075 .1 S
.0 .1 .2 .3 .4 A681
.0 .2 .4 .6 .8 MO
.0- O M -8-S- A- 16-
. O M S 8 A. 6 . . 61
. O M S . 8 A. 61 . .
. O M S . 8 A. 6 1 . .
. O MS . 8 A . 6 1 . .
. O SM . 8 A . 6 1 . .
. O S M . 8 A . 6 1 . .
. OS M . 8A . 6 1 . .
. S M . 8A .6 1 . . SO
. S O M . A8 6 1 . .
10.- -S-O- -M- A 8 -6- 1 -
.S O M. A 68 . 1 . .
.S O .M A 6 8 . 1 . .
.S O . A6 8 . 1 . . 6M
S O A6 M 8 . 1 . .
S OA6. 8 M . 1 . .
S AO . 8 M . 1 . . A6
S A O. 8 M .1 . . A6
S A 8 M1. . . A6,80
S A 8. O 1 M . . A6
50.S - -A- - 8 - - O - - - 1 - -M- - A6
S A 8 . O 1 . M . . A6
S A 8 . O1 . M . . A6
S A 8 . 1 O . M . . A6
S A 8 . 1 O . M . . A6
S A 8 1 O . M . . A6
.S A 8 1. O . M . . A6
.S A 8 1 . O . M . . A6
.S6A8 1 . C. M . .
90.- SA8 - - 1 - - - - - - - - - - O - -M- - - - - - - - - - - - - S6
. SA 1 . .O M . . S6,A8
. 6S 1 . . O M . . SA8
. 6S 1 . . OM . . SA8
. 6S 1 . . M . . SA,68,MO
. 6 S 1 . . M O . . SA,68
. 6 S1 . . M O . . SA,68
. 6 S1 . . M O . . SA,68
. 6 AS . .M O . . 68,S1
. 6 1S . M O . . SA,68
130.- 6 1S- - - - - - - - - - - - -M- - - - O - - - - - - - - - - - - SA,68
. 6 1 S . M. O . . SA,68
. 6 1 S . M . O . . SA,68
. 86 S . M . O . . SA,61
. 86 SA . M . O . . 61
. 86 SA . M . O . . 61
. 6 S . M . O . . SA,681
. 6 SA . M . O . . 681
. 6 SA . M . O . . 681
. 86 SA . M . O . . 81
170.- -86 -S-A- - - - - - M - - - - - - - - - -O- - - - - - - - - - - 61

7.6 The Salvage Mode (SALV)
(table 9 and figs. 59, 60, 61)

This extreme mode models an area that receives little or no management. Harvest is limited to removing trees at about 300 years of age in 1-acre openings.

Timber production is practically 0 for the first 100 years and eventually increases to about 0.2 of the maximum. As the harvest of timber in small openings increases, the index for sediment increases to the unacceptable level. Benefits are separated into two groups, those that are maximized and those that are minimized by the old-growth state of organization.

During the 90 years before harvesting begins, sediment stays at the base level and the indices for game species, except squirrel, are kept low by the lack of openings to provide soft mast. Later, the low production of hard mast by the old-growth habitat contributes to the low habitat indices.

A management policy for an area where very old timber is desired should probably use larger openings than those used in this illustration. Larger openings would improve the habitat indices for most animals and would reduce sedimentation.

Table 9.--Salvage mode (SALV 1/1). Data for the control of timber sales and information about the volumes of timber removed, the distribution of habitats, the indices for some benefits, number of openings per square mile, and the distribution of opening sizes. For definitions see appendix B.

Figure 59.--Salvage mode (SALV 1/1). The distribution of seedlings (S), saplings (A), 6-inch poles (6), 8-inch poles (8), 10-inch poles (1), mature timber (M), and old growth (O). Note the difference in scales which was necessary to illustrate the changes.

```
          DYNAST-MB 16 B.IVY ST    1/06/77 19:51   SALV 1/1

PTI=T,SEMT=I,BEAR=B,GRS=G,TUR=K,BLU=L,DEER=D,SQU=Q

        .0            .25            .5            .75            1. TIBGKLDQ
      .0TK- - - I - - - Q - - B - - - - D - - - - - - - G - - - - - - - TL
        TK       I     .  Q   D B     .             .  G           .  TL
        T K      I    D .   Q      B   .             .  G           .  TL
        T  K     I D     .    Q      B  .             .  G           .  TL
        T  K     D I     .      Q      B.             .  G           .  TL
        LT  K  DI        .        Q    B.             .   G          .
        LT  K D  I       .          Q   B.            .   G          .
        LT   K  I        .           Q  B.            .   G          .  KD
        LT  K      I     .             Q B            .   G          .  KD
        LT D K  I        .              QB            .   G          .
      10.LT-D-K- -I- - - - - - - - - - -B- - - - - - - - G - - - - - - - BQ
        LT   K     I     .                .B     Q      G              .  TD
        LT   K   I       .                .B          G  .              .  TD,GQ
        LT   K   I       .                B  .        G   Q .           .  TD
        LT   K   I       .             B     .    G        Q.           .  LD
        LT   K     I     .           B       G              Q           .  LD
        LT  K      I     .      B    G       .              .Q          .  LD
        LT   K   I       .   BG             .              . Q         .  LD
        LT   K   I      GB                  .              .   Q       .  LD
        LT   K   I  G    B                  .              .     Q     .  LD
      50.LT- - K IG- -B- - - - - - - - - - - - - - - - - - - - -Q- - - - LD
        LT     K I   B   .                  .              .       Q    . IG,LD
        LT    K G I B    .                  .              .         Q  . LD
        IT    KG    I    .                  .              .           Q. IB,LD
        LT    GK IB      .                  .              .            Q LD
        LT    G  I       .                  .              .            Q IB,GK,LD
        LT  G   B        .  I               .              .            Q GK,LD
        LDT G KB         .   I              .              .            Q
        LD T  B          .              I   .              .            Q TG,BK
        LD GTKB          .                  .           I  .            Q
      90.L DG-TB - - - - - - - - - - - - - - - - - - - I - - - - - - - Q BK
        L G   T B        .                  .              .     I      Q TK,GD
        L GD   TB        .                  .              .  I         Q BK
        L GD K TB        .                  .              .        I   Q
        L GD  K T        .                  .              .     I      Q TB
        L G D  KTB       .                  .              .     I      Q
        L G K    T B     .                  .              .            I KD,IQ
        .LG D    K T     .                  .              .      I     Q TB
        .LG   D K  TB    .                  .              .         I  Q
        L  G K      TB   .                  .              .            I KD,IQ
      130.L -G-K- - -T-B- - - - - - - - - - - - - - - - - - - - - - - - I KD,IQ
        .L G KD      T B.                  .              .            I IQ
        .L G  K      T  B                  .              .            I KD,IQ
        .L G KD      T  B                  .              .            I IQ
        .L  GKD       T .B                 .              .          QI
        .L  GKD         T.B                .              .        Q  I
        .L  G  D      T . B                .              .       Q   I GK
        .L  G  D       T. B                .              .      Q    I GK
        .L KG  D       T. B                .              .     Q     I
        .L  KG D         T  B              .              .    Q      I
      170.-L-K-G-D- - - -T- B - - - - - - - - - - - - - - - - Q - - - I
```

Figure 60.--Salvage mode (SALV 1/1). Changes in the indices for potential timber (T), sediment (I), bear (B), grouse (G), turkey (K), bluebird group (L), deer (D), and squirrels (Q).

```
          DYNAST-NB 16 B.IVY ST    1/06/77 19:51   SALV 1/1

VIS=V,UGI=U,CVN=O,PIL=P,FLIC=F,DON=N,TWE=W,PWE=E,HAR=H

      .0           .25           .5           .75           1. VUOPFNWEH
   .0UF- - W H -P- - - - - - - -V- - - - - - - - - - - - - - - N -O- PE
     UF    W  H  P  .      V      .                .          O  . ON,PE
     .U      W H P E.    V       .                .         ON  . UF
     .U        WH PVE            .                .       O  N  . UF
     .U       WVH  P. E          .                .      O    N . UF
     .U     V    WH P  E         .                .     O     N . UF
     .U   V       W  P    E      .                .    C      N . UF,PH
     .U   V        W .PH    E     .                .   O        N. UF
     U    V      W    . P  H  E  .                .  O         N. UF
     U    V       W   .  P   H  E .                . O          N UF
  10.U - -V- - -W- - - P - - H -E- - - - - - - - - -O- - - - - - N UF
     U  V     W       .     P     .  H  E       O.              N UF
     U  V    W        .        P  .        O  HE .              N UF
     U   V W           .           P  . O          .E  H         N UF
     U   VW            .           O P .           .  E    H     N UF
     U   V             .       O     .P            .    E    H  N UF,VW
     U   V             .   O         .  P          .         E  N UF,VW,NH
     U   V             .  O          .    P        .          E  N UF,VW,NH
     U  WV             O             .      P      .           E  N UF,NH
     U  WV           O .             .        P    .            E N UF,NH
  50.U -W-V- - - O - - - - - - - - - - - - - - -P- - - - - - - -EN UF,NH
     U W  V      O     .             .           P .              N UF,NEH
     U W  V     O      .             .           P                N UF,NEH
     U W  V     O      .             .          . P               N UF,NEH
     U W  V    O       .             .           .  P             N UF,NEH
     UW   V    O       .             .           .   P            N UF,NEH
     UW   V    O       .             .           .    P           N UF,NEH
     UW   V   O        .             .           .     P          N UF,NEH
     UW  V    O        .             .           .      P         N UF,NEH
     UW  V    O        .             .           .       P        N UF,NEH
  90.UW- V - O - - - - - - - - - - - - - - - - - - - - - - P - - N UF,NEH
     UW  V    O        .             .           .         P      N UF,NEH
     UW  V   O         .             .           .         P      N UF,NEH
     UW  V   O         .             .           .         P      N UF,NEH
     UW  V   O         .             .           .          P     N UF,NEH
     UFW V   O         .             .           .          P     N NEH
     UW  V   O         .             .           .          P     N UF,NEH
     UFW V   O         .             .           .           P    N NEH
     UFW V   O         .             .           .           P    N NEH
     UFW V    O        .             .           .           P    N NEH
 130.UFW V - O - - - - - - - - - - - - - - - - - - - - - - - -P- N NEH
     UFW V    O        .             .           .            P N NEH
     UF WV    O        .             .           .            P N NEH
     UFW V    O        .             .           .            PNE EH
     UF WV    O        .             .           .            P E PN,EH
     UF WV    O        .             .           .            P E PN,EH
     UF WV    O        .             .           .           N PE EH
     UF WV     O       .             .           .           N  PE EH
     UF WV     O       .             .           .           N  PE EH
     UF  V     O       .             .           .          N   PE VW,EH
 170.UF-WV - -O- - - - - - - - - - - - - - - - - - - - - - -N- -PE EH
```

Figure 61.--Salvage mode (SALV 1/1). Changes in the indices for visual variety (V), ugliness (U), ovenbird group (O), pileated woodpecker (P), flicker (F), downy (N), towhee group (W), pewee group (E), and hairy woodpecker (H).

APPENDIX A

A LIST OF THE DYNAST-MB EQUATIONS

See section 5.2 and figure 9 for information

```
      *  DYNAST-MB 16 B.IVY ST                                          01
      *  OLD GROWTH LOOP                                             00001
1     R  ROG.KL=OSA.K/DRT                                            00010
      C  DRT=2                                                       00011
2     L  OSA.K=OSA.J+DT*(OGS.JK-ROG.JK)                              00020
      N  OSA=OGS                                                     00021
3     R  OGS.KL=IOGS.K*FOG                                           00030
      N  FOG=(TAH*OGF)/(DOG+AOG)                                     00031
      N  TAH=ISE+ISA+IP6+IP8+IP1+IMT+IOG                             00032
      N  AMT=DSE+DSA+DP6+DP8+DP1                                     00033
      N  AOG=AMT+DMT                                                 00034
4     A  IOGS.K=TABHL(TIDM,COG.K,.5,2.5,.5)                          00040
      T  TIDM=0/1/1.1/1.2/1.3                                        00041
5     A  COG.K=OGR.K/EOG                                             00050
      N  EOG=FOG*DOG                                                 00051
      *  MATURE TIMBER LOOP                                          00052
6     R  RMT.KL=MHA.K/DRT                                            00060
7     L  MHA.K=MHA.J+DT*(MTS.JK-RMT.JK)                              00070
      N  MHA=MTS                                                     00071
8     R  MTS.KL=(MIN(HDI.K,IMTS.K))*FMT                              00080
      N  FMT=(TAH*(1-OGF))/(AMT+DMT)                                 00081
9     A  IMTS.K=TABHL(TIDM,CMT.K,.5,2.5,.5)                          00090
10    A  CMT.K=MTR.K/EMT                                             00100
      N  EMT=FDH*DMT                                                 00101
      N  FDH=FMT+FOG                                                 00102
11    A  HDI.K=TABHL(THDI,CDH.K,0,3,.5)                              00110
      T  THDI=1.3/1.3/1/.7/.4/.1/0                                   00111
12    A  CDH.K=SE.K/EDH                                              00120
      N  EDH=FDH*DSE                                                 00121
      *  TRANSFER TO OLD GROWTH                                      00122
13    R  TOG.KL=(MIN(IOGH.K,IMTS.K))*FOG                             00130
14    A  IOGH.K=TABHL(THDI,COG.K,0,3,.5)                             00140
      *  STATES OF SUCCESSION                                        00141
15    L  SE.K=SE.J+DT*(RMT.JK+ROG.JK-SSH.JK)                         00150
      N  SE=ISE                                                      00151
16    R  SSH.KL=SE.K/DSE                                             00160
17    L  SA.K=SA.J+DT*(SSH.JK-SPH.JK)                                00170
      N  SA=ISA                                                      00171
18    R  SPH.KL=SA.K/DSA                                             00180
19    L  P6.K=P6.J+DT*(SPH.JK-SP8.JK)                                00190
      N  P6=IP6                                                      00191
20    R  SP8.KL=P6.K/DP6                                             00200
21    L  P8.K=P8.J+DT*(SP8.JK-SP1.JK)                                00210
      N  P8=IP8                                                      00211
22    L  P1.K=P1.J+DT*(SP1.JK-SMT.JK)                                00220
23    R  SP1.KL=P8.K/DP8                                             00230
      N  P1=IP1                                                      00231
24    R  SMT.KL=P1.K/DP1                                             00240
25    L  MTR.K=MTR.J+DT*(SMT.JK-TOG.JK-MTS.JK)                       00250
      N  MTR=IMT                                                     00251
26    L  OGR.K=OGR.J+DT*(TOG.JK-CGS.JK)                              00260
      N  OGR=IOG                                                     00261
      *  SUPPLEMENTARY INFORMATION                                   00262
27    S  PSE.K=SE.K/TAH                                              00270
28    S  PSA.K=SA.K/TAH                                              00280
29    S  PP6.K=P6.K/TAH                                              00290
30    S  PP8.K=P8.K/TAH                                              00300
31    S  PP1.K=P1.K/TAH                                              00310
```

```
32    S  PMT.K=MT.K/TAH                                                    00320
33    S  MT.K=MTR.K+MHA.K                                                  00330
34    S  POG.K=OG.K/TAH                                                    00340
35    S  OG.K=OGR.K+OSA.K                                                  00350
36    S  PSEA.K=(SE.K+SA.K)/TAH                                            00360
37    S  PO8M.K=(P8.K+P1.K+MT.K)/TAH                                       00370
38    S  P1M.K=(P1.K+MT.K)/TAH                                             00380
39    S  PMO.K=(MT.K+OG.K)/TAH                                             00390
40    S  PSMT.K=RMT.JK/(RMT.JK+RCG.JK+E)                                   00400
      C  E=.01                                                             00401
41    S  PSOG.K=ROG.JK/(RMT.JK+RCG.JK+E)                                   00410
      *  SIZE AND NUMBER OF OPENINGS                                       00411
42    S  SOMT.K=NORMRN(ASOM.K,SDMT.K)                                      00420
43    S  ASOM.K=MIN(ISOM,RMT.JK)                                           00430
44    S  SDMT.K=MIN(ISDM,(RMT.JK/10))                                      00440
45    S  SOOG.K=NORMRN(ASOG.K,SDCG.K)                                      00450
46    S  ASOG.K=MIN(ISOG,ROG.JK)                                           00460
47    S  SDOG.K=MIN(ISDO,(ROG.JK/10))                                      00470
48    S  OPM.K=NOP.K/(TAH/640)                                             00480
49    S  NOP.K=(RMT.JK/(SOMT.K+E))+(ROG.JK/(SOOG.K+E))                     00490
50    S  OPS.K=(PSMT.K*SOMT.K)+(PSOG.K*SCOG.K)                             00500
      *  BENEFIT AND IMPACT EQUATIONS                                      00501
51    S  PTI.K=(TVO.K+TVM.K)/TIM                                           00510
52    S  TVO.K=ROG.JK*OGVF.K*OFOG.K                                        00520
53    S  TVM.K=RMT.JK*MTVF.K*OFMI.K                                        00530
      N  TIM=(TAH/TMR)*TYI                                                 00531
      N  TYI=TABHL(TTYI,TMR,20,320,30)                                     00532
      T  TTYI=.41/1/1.47/1.85/1.94/1.98/2.01/2.03/2.05/2.07/2.09           00533
54    S  MTVF.K=TABHL(TTYI,HAMT.K,20,320,30)                               00540
55    S  HAMT.K=(MT.K/FMT)+AMT                                             00550
56    S  OGVF.K=TABHL(TTYI,HAOG.K,20,320,30)                               00560
57    S  HAOG.K=(OG.K/FOG)+AOG                                             00570
58    S  OFMT.K=TABHL(TOFM,SOMT.K,0,3,.5)                                  00580
      T  TOFM=.5/.8/.9/.93/.95/.98/1                                       00581
59    S  OFOG.K=TABHL(TOFM,SOOG.K,0,3,.5)                                  00590
60    S  SEMT.K=TABHL(TSEMT,OPM.K,0,1,.2)                                  00600
      T  TSEMT=0/.3/.6/.8/.9/1                                             00601
61    S  UGL.K=UGS.K*UGN.K*UGO.K                                           00610
62    S  UGS.K=TABHL(TUGS,PSE.K,0,.06,.01)                                 00620
      T  TUGS=0/.1/.2/.3/.5/.7/1                                           00621
63    S  UGN.K=TABHL(TUGN,OPM.K,0,.8,.2)                                   00630
      T  TUGN=1/.9/.7/.4/.01                                               00631
64    S  UGO.K=TABHL(TUGO,OPS.K,0,30,3)                                    00640
      T  TUGO=0/.50/.65/.70/.75/.80/.85/.90/.95/.97/1                      00641
65    S  VIS.K=VSE.K*VBAL.K*VPOG.K                                         00650
66    S  VSE.K=TABHL(TVSE,PSE.K,.01,.07,.01)                               00660
      T  TVSE=.2/.6/.9/1/.9/.6/.2                                          00661
67    S  VBAL.K=TABHL(TVBA,BAL.K,0,2,.5)                                   00670
      T  TVBA=.4/.7/1/.7/.4                                                00671
68    S  BAL.K=(P8.K+P1.K+MT.K)/(SE.K+SA.K+P6.K)                           00680
69    S  VPOG.K=TABHL(TVPO,POG.K,0,.7,.1)                                  00690
      T  TVPO=.4/.7/.9/1/.9/.8/.6/.4                                       00691
70    S  DEER.K=HTD.K*OTD.K*DMA.K                                          00700
71    S  HTD.K=TABHL(THTD,PSE.K,0,.07,.01)                                 00710
      T  THTD=0/.1/.2/.5/.7/.8/.9/1                                        00711
72    S  OTD.K=TABHL(TOTD,OPS.K,0,60,6)                                    00720
      T  TOTD=1/1/.97/.93/.9/.85/.8/.7/.6/.5/.45                           00721
73    S  DMA.K=TABHL(TDMA,P1M.K,0,.2,.05)                                  00730
```

```
      T  TDMA=.1/.2/.5/.8/1                                                    00731
74    S  SQU.K=THS.K*SDT.K                                                     00740
75    S  THS.K=TABHL(TTHS,PO8M.K,0,.4,.1)                                      00750
      T  TTHS=0/.2/.4/.8/1                                                     00751
76    S  SDT.K=TABHL(TSDT,POG.K,0,.3,.1)                                       00760
      T  TSDT=.1/.7/.8/1                                                       00761
77    S  TUR.K=TURT.K*TURO.K                                                   00770
78    S  TURT.K=TABHL(TTRT,PO8M.K,0,.5,.1)                                     00780
      T  TTRT=0/.1/.2/.5/.8/1                                                  00781
79    S  TURO.K=TABHL(TTRO,OPS.K,0,28,2)                                       00790
      T  TTRO=0/.2/.5/.7/.9/1/1/1/1/.9/.8/.7/.6/.5/.4                          00791
80    S  GRS.K=GRH.K*GRO.K                                                     00800
81    S  GRH.K=TABHL(TGRH,PP6.K,0,.2,.05)                                      00810
      T  TGRH=0/.2/.7/.9/1                                                     00811
82    S  GRO.K=TABHL(TGRO,OPS.K,0,60,6)                                        00820
      T  TGRO=.8/.9/.95/1/.95/.9/.85/.8/.7/.6/.5                               00821
83    S  BEAR.K=BDT.K*BSMT.K*BHMT.K                                            00830
84    S  BDT.K=TABHL(TBDT,POG.K,0,.3,.1)                                       00840
      T  TBDT=.2/.8/.9/1                                                       00841
85    S  BSMT.K=TABHL(TBSM,PSEA.K,0,.2,.1)                                     00850
      T  TBSM=0/.5/1                                                           00851
86    S  BHMT.K=TABHL(TBHM,PO8M.K,0,.4,.1)                                     00860
      T  TBHM=0/.2/.4/.8/1                                                     00861
87    S  PIL.K=TABHL(TPIL,POG.K,0,.6,.1)                                       00870
      T  TPIL=.1/.4/.6/.8/.9/.95/1                                             00871
88    S  HAR.K=TABHL(THAR,PMO.K,0,.5,.05)                                      00880
      T  THAR=.05/.1/.15/.2/.35/.5/.65/.8/.9/.95/1                             00881
89    S  DON.K=TABHL(TDON,P1M.K,0,.4,.05)                                      00890
      T  TDON=.1/.15/.3/.4/.6/.8/.9/.95/1                                      00891
90    S  FLIC.K=FLF.K*FLN.K*FLO.K                                              00900
91    S  FLF.K=TABHL(TFLF,PSE.K,0,.06,.01)                                     00910
      T  TFLF=.05/.15/.3/.5/.7/.9/1                                            00911
92    S  FLN.K=TABHL(TFLN,PMO.K,0,.2,.05)                                      00920
      T  TFLN=.5/.8/.9/.95/1                                                   00921
93    S  FLO.K=TABHL(TFLO,OPS.K,0,10,2)                                        00930
      T  TFLO=.05/.1/.5/.9/.95/1                                               00931
94    S  BLU.K=BBH.K*BBO.K                                                     00940
95    S  BBH.K=TABHL(TBBH,PSE.K,0,.06,.01)                                     00950
      T  TBBH=0/.1/.2/.4/.7/.9/1                                               00951
96    S  BBO.K=TABHL(TBBO,OPS.K,0,60,6)                                        00960
      T  TBBO=0/.6/1/1/1/1/.95/.9/.85/.8/.7                                    00961
97    S  OVN.K=TABHL(TOVN,PP6.K,0,.3,.05)                                      00970
      T  TOVN=.1/.2/.4/.7/.8/.9/1                                              00971
98    S  TWE.K=TWH.K*TWO.K                                                     00980
99    S  TWH.K=TABHL(TTWE,PSA.K,0,.45,.05)                                     00990
      T  TTWE=0/.1/.2/.4/.6/.8/.85/.9/.95/1                                    00991
100   S  TWO.K=TABHL(TTWO,OPS.K,0,5,1)                                         01000
      T  TTWO=.1/.5/.7/.8/.9/1                                                 01001
101   S  PWE.K=TABHL(TPWE,PMO.K,0,.7,.1)                                       01010
      T  TPWE=.1/.2/.4/.7/.8/.9/.95/1                                          01011
102   S  VT.K=VOG.K+VMT.K                                                      01020
103   S  VOG.K=Y50*TVO.K                                                       01030
104   S  VMT.K=Y50*TVM.K                                                       01040
      C  Y50=2520                                                              01041
      *  INVENTORY AND CONTROLS                                                01042
      SPEC  DT=.25/LENGTH=170                                                  01043
105   A  PRTPER.K=1+STEP(39,11)                                                01050
      PRINT 1)OGS,VOG/2)MTS,VMT/3)PTI,VT/4)OG,MT/5)P1,P8/6)P6,SA/7)SE,SEMT/    01051
```

```
PRINT 8)DEER,SQU/9)TUR,GRS/10)VIS,UGL/11)BEAR,PIL/12)FLIC,DON/                01052
PRINT 13)TWE,NOP/14)OPM,OPS                                                   01053
A  PLTPER.K=1+STEP(3,11)                                                      01060
PLOT  PSE=S(0,.1)/PSA=A,PP6=6,PP8=8,PP1=1(0,.4)/PMT=M,POG=O(0,.8)             01061
PLOT  PTI=T,SEMT=I,BEAR=B,GRS=G,TUR=K,BLU=L,DEER=D,SQU=Q(0,1)                 01062
PLOT  VIS=V,UGL=U,OVN=O,PIL=P,FLIC=F,DON=N,TWE=W,PWE=E,HAR=H(0,1)             01063
C  DSE=5/DSA=30/DP6=15/DP8=15/DP1=20                                          01064
C  TMR=80                                                                    01065
C  ISE=200/ISA=1254/IP6=1843/IP8=740/IP1=1808/IMT=366/IOG=185  B.IVY,ST       01066
C  DMT=1/DOG=1/OGF=.01                        FAST                           01067
C  ISOM=45/ISDM=2/ISOG=10/ISDO=1                          45/10               01068
RUN   FAST 45/10                                                              01069
```

APPENDIX B

ALPHABETICAL LIST OF VARIABLES, NUMBER AND TYPE OF EQUATION WHERE FIRST DEFINED, DEFINITIONS, AND UNITS OF MEASURE

See section 5.2 and figure 9 for information

NAME	NO	T	DEFINITION
AMT	3.3	N	TRANSITION AGE MATURE (YEARS)
AOG	3.4	N	TRANSITION AGE OLD GROWTH (YEARS)
ASOG	46	S	AVERAGE SIZE OF OPENINGS OLD GROWTH (AREA)
ASOM	43	S	AVERAGE SIZE OPENINGS MATURE HABITAT (AREA)
BAL	68	S	BALANCE OF TALL AND SHORT HABITATS (DIMENSIONLESS)
BBH	95	S	BLUEBIRD HABITAT TYPE (DIMENSIONLESS)
BBO	96	S	BLUEBIRD OPENING TYPE (DIMENSIONLESS)
BDT	84	S	BEAR DEN HABITAT (DIMENSIONLESS)
BEAR	83	S	BEAR HABITAT INDEX (DIMENSIONLESS)
BHMT	86	S	BEAR HARD MAST TYPE (DIMENSICNLESS)
BLU	94	S	BLUEBIRD HABITAT INDEX (DIMENSIONLESS)
BSMT	85	S	BEAR SOFT MAST TYPE (DIMENSIONLESS)
CDH	12	A	COVERAGE OF DIVERTED HABITATS (DIMENSIONLESS)
CMT	10	A	COVERAGE OF MATURE HABITAT (DIMENSIONLESS)
COG	5	A	COVERAGE OF OLD GROWTH HABITAT (DIMENSIONLESS)
DEER	70	S	DEER HABITAT INDEX (DIMENSIONLESS)
DMA	73	S	DEER MAST AVAILABILITY (DIMENSIONLESS)
DMT	106.7	C	DELAY FOR MATURE HABITAT SUCCESSION (YEARS)
DOG			DELAY FOR OLD GROWTH SUCCESSION (YEARS)
DON	89	S	DOWNY WOODPECKER HABITAT INDEX (DIMENSIONLESS)
DP1			DELAY FOR POLE-10 SUCCESSION (YEARS)
DP6			DELAY FOR POLE-6 SUCCESSION (YEARS)
DP8			DELAY FOR POLE-8 SUCCESSION (YEARS)
DRT	1.1	C	DELAY FOR REMOVAL OF TIMBER (YEARS)
DSA			DELAY FOR SAPLING SUCCESSION (YEARS)
DSE	106.4	C	DELAY FOR SEEDLING SUCCESSION (YEARS)
E	40.1	C	EQUILIBRIUM CONSTANT (DIMENSION OF VARIABLE)
EDH	12.1	N	EQUILIBRIUM DIVERTED HABITAT (AREA)
EMT	10.1	N	EQUILIBRIUM MATURE HABITAT (AREA)
EOG	5.1	N	EQUILIBRIUM OLD GROWTH HABITAT (AREA)
FDH	10.2	N	FLOW DIVERTED HABITATS (AREA/YEAR)
FLF	91	S	FLICKER FOOD HABITAT (DIMENSIONLESS)
FLIC	90	S	FLICKER WOODPECKER HABITAT INDEX (DIMENSIONLESS)
FLN	92	S	FLICKER NESTING HABITAT (DIMENSIONLESS)
FLC	93	S	FLICKER OPENING HABITAT (DIMENSIONLESS)
FMT	8.1	N	FLOW MATURE TIMBER HABITATS (AREA/YEAR)
FOG	3.1	N	FLOW OLD GROWTH HABITATS (AREA/YEAR)
GRH	81	S	GROUSE HABITAT TYPE (DIMENSIONLESS)
GRO	82	S	GROUSE OPENING TYPE (DIMENSIONLESS)
GRS	80	S	GROUSE HABITAT INDEX (DIMENSIONLESS)
HAMT	55	S	HARVEST AGE MATURE TIMBER (YEARS)
HAOG	57	S	HARVEST AGE OLD GROWTH (YEARS)
HAR	88	S	HAIRY WOODPECKER HABITAT INDEX (DIMENSIONLESS)
HDI	11	A	HABITAT DIVERSION INDICATED (DIMENSIONLESS)
HTD	71	S	HABITAT TYPE DEER (DIMENSIONLESS)
IMT			INVENTORY MATURE TIMBER (AREA)
IMTS	9	A	INDICATED MATURE TIMBER SALES (DIMENSIONLESS)
IOG			INVENTORY OLD GROWTH (AREA)

IOGH	14	A	INDICATED OLD GROWTH HABITAT (DIMENSIONLESS)
IOGS	4	A	INDICATED OLD GROWTH SALES (DIMENSIONLESS)
IP1			INVENTORY POLE-10 (AREA)
IP6			INVENTORY POLE-6 (AREA)
IP8			INVENTORY POLE-8 (AREA)
ISA			INVENTORY SAPLINGS (AREA)
ISDM			DESIRED STANDARD DEVIATION OPENINGS MATURE HABITAT (AREA)
ISDO			DESIRED STANDARD DEVIATION OPENINGS OLD GROWTH (AREA)
ISE	106.6	C	INVENTORY SEEDLINGS (AREA)
ISOG			DESIRED AVERAGE SIZE OF OPENING OLD GROWTH (AREA)
ISOM	106.8	C	DESIRED AVERAGE SIZE OF OPENING MATURE HABITAT (AREA)
LENGTH			
MHA	7	L	MATURE HABITAT SALES ACCUMULATION (AREA)
	7.1	N	
MIN			FUNCTION SELECTS MINIMUM VALUE
MT	33	S	MATURE TIMBER HABITAT (AREA)
MTR	25	L	MATURE TIMBER RESERVES (AREA)
	25.1	N	
MTS	8	R	MATURE TIMBER SALES (AREA/YEAR)
MTVF	54	S	MATURE TIMBER VOLUME FACTOR (VOLUME UNITS/ AREA)
NOP	49	S	NUMBER OF OPENINGS (NUMBER)
NORMRN			NORMAL DEVIATE RANDOM NUMBER FUNCTION
OFMT	58	S	OPENING FACTOR MATURE TIMBER (DIMENSIONLESS)
OFOG	59	S	OPENING FACTOR OLD GROWTH (DIMENSIONLESS)
OG	35	S	OLD GROWTH HABITAT (AREA)
OGF			FRACTION REMOVED THRCUGH OLD GROWTH HABITAT (PERCENT)
OGR	26	L	OLD GROWTH RESERVES (AREA)
	26.1	N	
OGS	3	R	OLD GROWTH SALES (AREA/YEAR)
OGVF	56	S	OLD GROWTH VOLUME FACTOR (VOLUME UNITS/ AREA)
OPM	48	S	NUMBER OF OPENINGS PER SQUARE MILE (NUMBER/ SQUARE MILE)
OPS	50	S	OPENING SIZE DISTRIBUTION (PROPORTIONAL AREA)
OSA	2	L	OLD GROWTH SALES ACCUMULATION (AREA)
	2.1	N	
OTD	72	S	OPENING TYPE DEER (DIMENSIONLESS)
OVN	97	S	OVENBIRD HABITAT INDEX (DIMENSIONLESS)
PIL	87	S	PILEATED WOODPECKER HABITAT INDEX (DIMENSIONLESS)
PLTPER	106	A	
PMO	39	S	PROPORTION OF AREA IN MATURE AND OLD GROWTH HABITATS (PERCENT)
PMT	32	S	PROPORTION OF AREA IN MATURE TIMBER HABITAT (PERCENT)
POG	34	S	PROPORTION OF AREA IN OLD GROWTH HABITAT (PERCENT)

P08M	37	S	PROPORTION OF AREA IN POLE-8,POLE-10 AND MATURE HABITATS(PERCENT)
PP1	31	S	PROPORTION OF AREA IN POLE-10 HABITAT (PERCENT)
PP6	29	S	PROPORTION OF AREA IN POLE-6 HABITAT (PERCENT)
PP8	30	S	PROPORTION OF AREA IN POLE-8 HABITAT (PERCENT)
PRTPER	105	A	
PSA	28	S	PROPORTION OF AREA IN SAPLING HABITAT (PERCENT)
PSE	27	S	PROPORTION OF AREA IN SEEDLING HABITAT (PERCENT)
PSEA	36	S	PROPORTION OF AREA IN SEEDLINGS AND SAPLINGS (PERCENT)
PSMT	40	S	PROPORTION OF SALES FROM MATURE TIMBER (PERCENT)
PSOG	41	S	PROPORTION OF SALES FROM OLD GROWTH (PERCENT)
PTI	51	S	POTENTIAL TIMBER INDEX (DIMENSIONLESS)
PWE	101	S	PEEWEE HABITAT INDEX (DIMENSIONLESS)
P1	22	L	POLE 10-INCH HABITAT (AREA)
	23.1	N	
P1M	38	S	PROPORTION OF AREA IN POLE-10 AND MATURE HABITATS (PERCENT)
P6	19	L	POLE 6-INCH HABITAT (AREA)
	19.1	N	
P8	21	L	POLE 8-INCH HABITAT (AREA)
	21.1	N	
RMT	6	R	REMOVE MATURE HABITAT (AREA/YEAR)
ROG	1	R	REMOVE OLD GROWTH (AREA/YEAR)
SA	17	L	SAPLING HABITAT (AREA)
	17.1	N	
SDMT	44	S	STANDARD DEVIATION OPENINGS MATURE HABITAT (AREA)
SDOG	47	S	STANDARD DEVIATION OPENINGS OLD GROWTH (AREA)
SDT	76	S	SQUIRREL DEN TREE INDEX (DIMENSIONLESS)
SE	15	L	SEEDLING HABITAT (AREA)
	15.1	N	
SEMT	60	S	SEDIMENT INDEX (DIMENSIONLESS)
SMT	24	R	SUCCESSION TO MATURE TIMBER (AREA/YEAR)
SOMT	42	S	SIZE OF OPENINGS IN MATURE HABITAT (AREA)
SOOG	45	S	SIZE OF OPENINGS IN OLD GROWTH (AREA)
SPH	18	R	SUCCESSION TO POLE HABITAT (AREA/YEAR)
SP1	23	R	SUCCESSION TO POLE-10 (AREA/YEAR)
SP8	20	R	SUCCESSION TO POLE-8 (AREA/YEAR)
SQU	74	S	SQUIRREL HABITAT INDEX (DIMENSIONLESS)
SSH	16	R	SUCCESSION TO SAPLING HABITAT (AREA/YEAR)
TAH	3.2	N	TOTAL AREA ALL HABITATS (AREA)
TBBH	95.1	T	TABLE BLUEBIRD HABITAT
TBBO	96.1	T	TABLE BLUEBIRD OPENING
TBDT	84.1	T	TABLE BEAR DEN TYPE
TBHM	86.1	T	TABLE BEAR HARD MAST

TBSM	85.1	T	TABLE BEAR SOFT MAST
TDMA	73.1	T	TABLE DEER MAST AVAILABILITY
TDCN	89.1	T	TABLE DOWNY WOODPECKER
TFLF	91.1	T	TABLE FLICKER FOOD
TFLN	92.1	T	TABLE FLICKER NESTING
TFLO	93.1	T	TABLE FLICKER OPENING
TGRH	81.1	T	TABLE GROUSE HABITAT
TGRO	82.1	T	TABLE GROUSE OPENINGS
THAR	88.1	T	TABLE HAIRY WOODPECKER
THDI	11.1	T	TABLE HABITAT DIVERSION (DIMENSIONLESS)
THS	75	S	TYPE HABITAT FOR SQUIRRELS (DIMENSIONLESS)
THTD	71.1	T	TABLE HABITAT TYPE DEER
TIDM	4.1	T	TABLE INDICATED DIVERSION TIMBER (DIMENSIONLESS)
TIM	53.1	N	TIMBER INDEX MAXIMUM (VOLUME UNITS)
TMR	106.5	C	TIMBER MAXIMUM ROTATION AGE (YEARS)
TOFM	58.1	T	TABLE OPENING FACTOR MULTIPLIER (DIMENSIONLESS)
TOG	13	R	TRANSFER TO OLD GROWTH (AREA/YEAR)
TOTD	72.1	T	TABLE OPENING TYPE DEER
TOVN	97.1	T	TABLE OVENBIRD
TPIL	87.1	T	TABLE PILEATED WOODPECKER
TPWE	101.1	T	TABLE PEEWEE HABITAT
TSDT	76.1	T	TABLE SQUIRREL DEN TREE
TSEMT	60.1	T	TABLE SEDIMENT INDEX
TTHS	75.1	T	TABLE TYPE HABITAT SQUIRRELS
TTRO	79.1	T	TABLE TURKEY OPENINGS
TTRT	78.1	T	TABLE TURKEY TYPE
TTWE	99.1	T	TABLE TOWHEE HABITAT
TTWO	100.1	T	TABLE TOWHEE OPENING
TTYI	53.3	T	TABLE TIMBER YIELD INDEX (VOLUME UNITS/UNIT AREA/YEAR)
TUGN	63.1	T	TABLE UGLY FOR NUMBER OF OPENINGS
TUGO	64.1	T	TABLE UGLINESS DUE TO OPENING SIZE
TUGS	62.1	T	TABLE UGLY FOR SEEDLINGS
TUR	77	S	TURKEY HABITAT INDEX (DIMENSIONLESS)
TURO	79	S	TURKEY OPENING INDEX (DIMENSIONLESS)
TURT	78	S	TURKEY TYPE HABITAT (DIMENSIONLESS)
TVBA	67.1	T	TABLE VISUAL FOR BALANCE
TVM	53	S	TIMBER VOLUME MATURE TIMBER (VOLUME UNITS)
TVO	52	S	TIMBER VOLUME OLD GROWTH (VOLUME UNITS)
TVPO	69.1	T	TABLE VISUAL OLD GROWTH
TVSE	66.1	T	TABLE VISUAL DUE TO SEEDLINGS
TWE	98	S	TOWHEE HABITAT INDEX (DIMENSIONLESS)
TWH	99	S	TOWHEE HABITAT TYPE (DIMENSIONLESS)
TWO	100	S	TOWHEE OPENING TYPE (DIMENSIONLESS)
TYI	53.2	N	TIMBER YIELD INDEX (VOLUME UNITS/UNIT AREA/YEAR)
UGL	61	S	UGLINESS INDEX (DIMENSIONLESS)
UGN	63	S	UGLY DUE TO NUMBER OF OPENINGS (DIMENSIONLESS)
UGO	64	S	UGLINESS DUE TO OPENING SIZE DISTRIBUTION (DIMENSIONLESS)
UGS	62	S	UGLY DUE TO SEEDLINGS (DIMENSIONLESS)
VBAL	67	S	VISUAL APPEAL DUE TO BALANCED CONTRAST (DIMENSIONLESS)
VIS	65	S	VISUAL APPEAL INDEX (DIMENSIONLESS)

VMT	104	S	VOLUME HARVESTED MATURE TIMBER (CUBIC VOLUME)
VOG	103	S	VOLUME HARVESTED OLD GROWTH (CUBIC VOLUME)
VPOG	69	S	VISUAL DUE TO OLD GROWTH HABITATS (DIMENSIONLESS)
VSE	66	S	VISUAL DUE TO SEEDLING HABITAT (DIMENSIONLESS)
VT	102	S	VOLUME HARVESTED TOTAL TIMBER (CUBIC VOLUME)
Y50	104.1	C	YIELD TABLE VOLUME, AGE 50 (CUBIC VOLUME)

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Insect Attacks on and Mortality of Slash and Longleaf Pines Treated with Paraquat to Induce Lightwood Formation

Abstract.--Six studies were conducted in north Florida from April 1974 to January 1976 to evaluate the effects of various paraquat application methods on subsequent insect attacks and tree mortality in slash and longleaf pines. The principal findings were that tree mortality was reduced: (1) when paraquat treatments were applied in November and January, (2) when bark-streak wound width was reduced from $\frac{2}{3}$ tree circumference to $\frac{1}{3}$ circumference, (3) when paraquat concentration was reduced from 8 percent to 2 percent, (4) when bark-streak wounds were used instead of ax-frill wounds, and (5) when the basal 1 m of the tree was sprayed with 1 percent BHC or lindane water emulsion immediately after paraquat application. Small field studies showed that the ambrosia beetle, Platypus flavicornis (F.), was attracted to freshly made wounds on slash pine only when paraquat was applied directly to the wound.

Keywords: Pinus elliottii, P. palustris, ambrosia beetle, black turpentine beetle, Ips.

Since the discovery that the herbicide paraquat[2] induced lightwood formation (pitch soaking of the xylem) in southern pines (Roberts 1973), a variety of bark beetles, ambrosia beetles, and wood-boring beetles have been found in dead and dying paraquat-treated trees. The ambrosia beetle, Platypus flavicornis (F.), (Coleoptera:Platypodidae) and the black turpentine beetle, Dendroctonus terebrans (Olivier), (Coleoptera:Scolytidae) attack paraquat-treated trees at the base. Ambrosia beetles attack up to 0.3 m above ground, while black turpentine beetles attack as high as 2 m. The Ips spp. bark beetles (Coleoptera:Scolytidae) and wood borers (Coleoptera:Buprestidae and Cerambycidae) are usually found above 2 m. Black turpentine beetle and Ips beetle attacks are easily recognized by pitch tubes and reddish-brown boring dust in the bark crevices, while ambrosia attacks can be recognized by the white, finely shredded frass which accumulates at the base of the tree. Buprestid and cerambycid attacks are identified by the egg niches made by female beetles on the bark surface.

The six studies described in this Paper were established between April 1974 and January 1975, and each continued until January 1976. Studies were designed to answer the following questions:

1. Does tree mortality vary with the season of paraquat application?

2. How do degree of wounding, paraquat concentration, and wound type affect tree mortality?

3. Are ambrosia beetles attracted by wounds on pines, by paraquat, or by both in combination?

Since the purposes of the studies varied widely, each study and its results will be described separately. The general study methods common to all studies are described below.

[2]Chemical name: dichloride salt of 1, 1′-dimethyl-4, 4′-bipyridylium.

GENERAL STUDY METHODS

Basal, horizontal tree wounds of various lengths were made with a motorized, rotary chipping tool (Clements and McReynolds 1977). All wounds were 0.3 m from the ground. With this tool a 2.54-cm-wide streak of outer and inner bark was removed, exposing the wood (xylem). About 2 ml of paraquat solution was applied to each wound with the same plastic squeeze bottle used to apply sulfuric acid to naval stores trees (Schopmeyer 1947). Where insecticides were used, the chemical was applied to the bark surface from ground line to 1 m in height with a 3-gallon, hand-pumped, compressed-air sprayer.

When insect attacks were in progress, study trees were observed at approximately weekly intervals. During the winter (December to March), observations were made once a month. No effort was made to quantify insect attacks or subsequent insect development and emergence.

SLASH PINE MORTALITY RELATED TO SEASON OF PARAQUAT APPLICATION

METHODS

Two 16-year-old plantations of slash pine (Pinus elliottii Engelm. var. elliottii) were treated--one in Columbia County, Florida, on Owens-Illinois, Inc., land and one in Taylor County, Florida, on Buckeye Cellulose Corporation land. Data for each location were analyzed separately by analysis of variance and Tukey multiple comparison procedures. Diameter at breast height (d.b.h.) averaged 15.5 cm and ranged from 8.9 to 26.4 cm. Two plots were installed at each location in April, July, and November 1974 and in January 1975. Each plot (replicate) consisted of six 20-tree rows to which treatments were assigned randomly as follows:

1. Check--no wound; no paraquat; no insecticide

2. $\frac{1}{3}$-circumference bark-streak wound and 8 percent paraquat

3. $\frac{1}{3}$-circumference wound; 8 percent paraquat; 1 percent BHC[3] w.e. (water emulsion)

4. $\frac{1}{2}$-circumference wound and 8 percent paraquat

5. $\frac{1}{2}$-circumference wound; 8 percent paraquat; 1 percent BHC w.e.

6. $\frac{1}{2}$-circumference wound only.

RESULTS

In both study areas tree mortality was greatest after the April applications of paraquat and decreased in the order: April > July > January > November (fig. 1). The significantly lower mortality following the November application probably was largely due to decreased insect activity during the winter.

[3]Chemical name: 1,2,3,4,5,6-hexachlorocyclohexane.

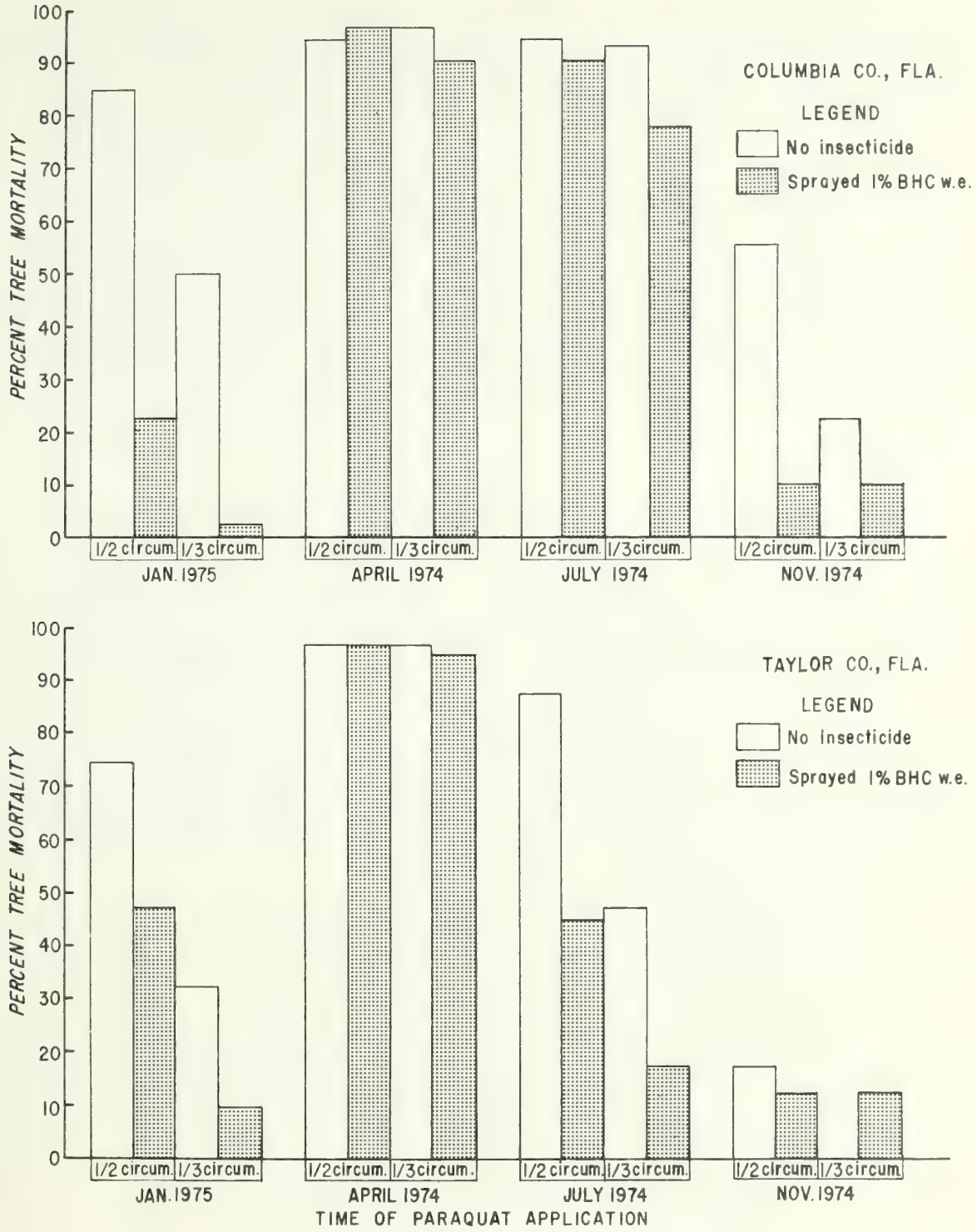

Figure 1.--Effects of 8 percent paraquat applied at different times of the year to two wound sizes, with and without insecticide treatment, on the mortality of 16-year-old planted slash pines in Columbia and Taylor Counties, Florida, January 1976.

From the standpoint of tree mortality from the insect-paraquat interactions, November application appears best. A particular season of application cannot be recommended, however, because we do not know how season of treatment affects lightwood formation.

All treatments in which paraquat was applied to the wound caused significant tree mortality. Spraying 1 percent BHC on tree bases reduced mortality, but results varied by study area and by plot within areas (fig. 1).

At both study locations, tree mortality was highest when 8 percent paraquat was applied to a $\frac{1}{2}$-circumference wound and when no BHC was applied. Treatments causing the next severest tree mortality were the $\frac{1}{3}$-circumference wound/8 percent paraquat/no insecticide, and $\frac{1}{2}$-circumference wound/8 percent paraquat/1 percent BHC; however, these treatments did not differ significantly from each other at either study location. Of all trees treated with paraquat, lowest mortality occurred in the $\frac{1}{3}$-circumference/8 percent paraquat/1 percent BHC treatment.

In Columbia County, within 4 months after the April and July applications of paraquat to $\frac{1}{2}$- and $\frac{1}{3}$-circumference wounds (without insecticide), more than 50 percent of the trees had died. Only those pines receiving a $\frac{1}{2}$-circumference wound in November reached 50 percent mortality (11 months after treatment). Of the trees treated in January, 50 percent with $\frac{1}{2}$-circumference wounds died within 6 months and 50 percent with $\frac{1}{3}$-circumference wounds died by within 7 months.

In Taylor County it took only 3 months for 50 percent of the pines to die from $\frac{1}{2}$- and $\frac{1}{3}$-circumference wounds made in April. Trees with $\frac{1}{2}$-circumference wounds made in July suffered 50 percent mortality within 4 months, while those with similar wounds made in January took 7 months to reach 50 percent. All other paraquat treatments without insecticides sustained less than 50 percent mortality.

After paraquat treatments in November and January, trees continued to die for up to 1 year, but mortality was less than after April and July treatments.

Insect attacks were observed but not counted. The first attacks by all major insects occurred within 1 month when paraquat was applied in April or July. Because of the cool weather, the trees treated in the winter took longer to come under attack. As expected, those treatments with the most trees under attack suffered greatest tree mortality. Black turpentine beetle and ambrosia beetle attacks were reduced by basal applications of BHC.

SLASH PINE MORTALITY FROM VARIOUS CONCENTRATIONS OF PARAQUAT ON $\frac{1}{3}$- CIRCUMFERENCE WOUNDS

METHODS

One plot was established in a 16-year-old slash pine plantation in Columbia County, Florida; d.b.h. averaged 14.7 cm and ranged from 9.7 to 16.0 cm. This design consisted of fourteen 10-tree rows, side by side. Treatments were

assigned at random to two rows each: (1) check, (2) wound only, (3) 0.5 percent paraquat on wound, (4) 2.0 percent paraquat on wound, (5) 8 percent paraquat on wound; 1 percent lindane[4] was applied to bases of wounded trees treated with paraquat in half the rows. All wounds covered one-third of the tree circumference. In the 0.5 percent and 2 percent paraquat treatments, lindane was applied only to one 10-tree row each.

Tree mortality increased with paraquat concentration (table 1). When lindane was sprayed onto bases of trees, only those treated with 8 percent paraquat died. Mortality of trees treated with 8 percent paraquat occurred during the same growing season. When 2.0 percent paraquat was applied without insecticide spraying, 60 percent of the trees died during the second growing season. Ninety-five percent of the trees treated with 8 percent paraquat (with no insecticide) died by December of the first year.

Table 1.--Sixteen-year-old slash pines killed by paraquat and/or insects 19 months after treatment with paraquat and lindane in Columbia County, Florida, December 1975

Paraquat[1] concentration (percent)	$\frac{1}{3}$-circumference bark-chip		No wound[3]
	No lindane[2]	1 percent lindane[2]	
	- - - Percent - - -		
0	0	--	0
.5	25	0	--
2	60	0	--
8	100	50	--

[1] Applied May 30, 1974.
[2] Twenty trees/treatment = two 10-tree rows.
[3] Ten trees/treatment.

SLASH PINE MORTALITY RELATED TO PARAQUAT CONCENTRATION AND WOUND SIZE

METHODS

A plot with twenty-two 10-tree rows side by side was established in a slash pine plantation in Columbia County, Florida; d.b.h. averaged 15.5 cm and ranged from 11.9 to 18.3 cm. On June 6, 1974, 2 and 4 percent paraquat were

[4] Gamma isomer of benzene hexachloride (1, 2, 3, 4, 5, 6-hexachlorocyclohexane).

applied to wounds covering $\frac{1}{3}$, $\frac{1}{2}$, $\frac{2}{3}$, and $\frac{1}{3} + \frac{1}{3}$ on opposite sides of tree circumferences. There were two check rows and two rows of each concentration-wound combination. One of the two rows in each treatment was sprayed with a 1 percent lindane w.e. A wound-only row for each wound size was also included. Each treatment was assigned randomly to a row.

RESULTS

Without lindane applications, tree mortality exceeded 50 percent with the smallest wound size ($\frac{1}{3}$-circumference) and lowest (2 percent) paraquat concentration (table 2). With lindane, tree mortality reached 50 percent only when 4 percent paraquat was applied to double $\frac{1}{3}$-circumference wounds.

Table 2.--Sixteen-year-old slash pines killed by paraquat and/or insects 18 months after treatment. Variables were wound size, paraquat concentration, and lindane application in Columbia County, Florida

Treatments[1]	Percent paraquat concentration		
	0.0	2.0	4.0
	- - - - - Percent - - - - -		
$\frac{1}{3}$-circum. wound:			
No lindane	0	60	80
1 percent lindane w.e.	--	10	10
$\frac{1}{2}$-circum. wound:			
No lindane	20	70	100
1 percent lindane	--	0	20
$\frac{2}{3}$-circum. wound:			
No lindane	10	100	100
1 percent lindane	--	10	40
$\frac{1}{3}$-circum. wound (both sides):			
No lindane	10	100	100
1 percent lindane	--	30	50
No wound, paraquat, or lindane	0	--	--

[1] Ten trees/treatment applied June 6, 1974.

By June 20, the black turpentine beetle had attacked trees in all treatments, including those trees treated with lindane. It was not until July 12 that trees without lindane came under attack by Ips. By July 5, all non-lindane-treated trees had come under attack by ambrosia beetles.

PINE MORTALITY IN A PLANTATION AND IN NATURAL STANDS RELATED TO PARAQUAT CONCENTRATION, WOUND SIZE, AND WOUNDING METHOD

PLANTATION (SLASH)

Methods

One 600-tree plot was established in an 18-year-old slash pine plantation on June 18, 1974, in Calhoun County, Florida, in cooperation with Reichhold Chemicals, Inc. Tree d.b.h. averaged 20.1 cm and ranged from 12.7 to 34.0 cm. The treatments were all combinations of two wounding methods (ax-chop and bark-chip), four paraquat concentrations (0.5, 2, 4, and 8 percent), and three wound sizes ($\frac{1}{6}$-, $\frac{1}{3}$-, and $\frac{2}{3}$- circumference). Wound-only trees were also included. All 30 treatments were assigned at random to the first 300 trees; then the trees were sprayed with 0.5 percent BHC w.e. The same treatments were assigned to the next 300 trees, but these trees were not sprayed with BHC. The study plan specified 10 trees per treatment, but due to error in recording treatment assignments, the number of trees per treatment varied from 6 to 13.

Results

Substantial tree mortality occurred in all paraquat treatments (table 3). Even those trees with a $\frac{2}{3}$-circumference wound and no paraquat applied suffered some mortality. The 0.5 percent BHC application reduced tree mortality markedly in all treatments. Mortality was also much lower among trees with bark-chip wounds than among those with ax-chop wounds; this may be due to larger amounts of paraquat puddling in the bottom of the cleft wound made by the ax.

Table 3.--Eighteen-year-old slash pines killed by paraquat and/or insects 18 months after treatment. Variables were wounding method, wound size, paraquat concentration, and BHC application in Calhoun County, Florida, December 1975

PLANTED[1]

Paraquat concentration (percent)	Ax-chop wound						Bark-chip wound					
	$\frac{1}{6}$-circum.		$\frac{1}{3}$-circum.		$\frac{2}{3}$-circum.		$\frac{1}{6}$-circum.		$\frac{1}{3}$-circum.		$\frac{2}{3}$-circum.	
	No BHC	0.5% BHC	No BHC	0.5% BHC	No BHC	0.5% BHC	No BHC	0.5% BHC	No BHC	0.5% BHC	No BHC	0.5% BHC
	Percent											
0 (wound only)	0	10	0	0	23.1	0	0	0	10	0	14.3	0
.5	9.1	0	36.4	0	100	10	0	10	22.2	0	54.5	20
2	37.5	0	57.1	0	75	20	8.3	0	23.1	0	38.5	0
4	33.3	0	44.4	20	100	30	9.1	0	27.3	0	40	20
8	36.4	20	71.4	40	100	70	22.2	10	16.7	0	66.7	30

NATURAL[2]

0 (wound only)	0	0	0	0	0	0	0	0	0	0	0	0
.5	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	20	0	0	0	0	0	0	0	20	0
4	0	0	0	0	20	0	0	0	20	0	0	0
8	20	0	25	25	100	100	0	0	16.7	50	40	25

[1] Treatments applied June 18, 1974.
[2] Ten trees/treatment; applied June 18, 1974.

NATURAL STAND (SLASH AND LONGLEAF)

Methods

Two 300-tree plots (one in slash pine and one in longleaf pine) were established June 19, 1974, in Calhoun County, Florida, in cooperation with Reichhold Chemicals, Inc. The 18-year-old slash pine stand had a density of 300 trees/ha and trees averaged 19.1 cm d.b.h. The 35-year-old longleaf pine stand had a density of 269 trees/ha and trees averaged 32.3 cm d.b.h. Wound types, paraquat concentrations, and wound sizes were the same as in the 18-year-old plantation just described.

Results, Slash Pine

There was little mortality except in trees receiving the largest wounds and highest concentrations of paraquat (table 3).

Results, Longleaf Pine

Wounding alone killed no pines during the first year. None of the trees with $\frac{1}{6}$- or $\frac{1}{3}$-circumference ax-chop wounds died. Mortality of trees with $\frac{2}{3}$-circumference wounds to which 2, 4, and 8 percent paraquat were applied was 20, 20, and 60 percent, respectively. The only BHC-treated trees to die (60 percent) were those with a $\frac{2}{3}$-circumference ax-chop wound and an 8 percent paraquat application.

RESPONSE OF AMBROSIA BEETLES TO PARAQUAT-TREATED SLASH PINES

Two studies were conducted in a 16-year-old slash pine plantation in Columbia County, Florida, during the summer of 1974 to evaluate the response of the ambrosia beetles, P. flavicornis (F.), to various wound and paraquat combinations. This plantation was owned by Owens-Illinois, Inc.

STUDY 1 METHODS

In the first study, four rows of four trees each were selected, and the following four treatments were randomly assigned:

1. No wound; no paraquat
2. No wound; 8 percent paraquat on bark
3. $\frac{1}{3}$-circumference bark-chip wound at 22.9-cm height; no paraquat
4. $\frac{1}{3}$-circumference bark-chip wound at 22.9-cm height; 8 percent paraquat.

All treatments were applied on the north sides of trees on May 16.

Prior to treatment, a 0.3-m^2 area of rough bark was smoothed off (rossed). The base of the rossed area was 7.6 cm above the ground and extended to 38.1 cm. In treatments 3 and 4, a 2.54-cm-wide streak was made with a mechanized, rotary chipping tool on the rossed area at 22.9 cm above the

ground and encompassed one-third of the tree's circumference. Two ml of 8 percent paraquat w.e. was applied to the wound in treatment 4 and on the area of bark where the wound would have been in treatment 2.

Tree Tanglefoot®[5] (a sticky compound for trapping insects) was then applied to the rossed area. The wounds in treatments 3 and 4 and the areas that would have been wounded in treatment 2 were not sprayed with Tanglefoot. At weekly intervals thereafter, ambrosia beetles were collected from the sticky surface.

RESULTS

One ambrosia beetle was collected from the sticky area on trees with no paraquat; 4 on two trees with paraquat applied to the bark; 6 on three trees having only a wound; and 3,825 on the four wounded trees on which paraquat was applied. Monthly totals show that beetles were most active in June, July, and August (table 4). These results suggest that paraquat reacting with the freshly exposed xylem and/or inner phloem tissues attracts the beetles, possibly by eliciting an olfactory response. The factors responsible for attraction to the paraquat-treated host trees remain to be determined.

Table 4.--Ambrosia beetles collected each month on 0.3-m^2 areas sprayed with Tree Tanglefoot® around 2.54-cm-wide, $\frac{1}{3}$-circumference wounds sprayed with 2 ml of 8 percent paraquat. Trees were 16-year-old slash pines in Columbia County, Florida

Months	Tree number				Total
	1	2	3	4	
	Number				
May	64	11	124	24	223
June	378	415	316	357	1,466
July	335	473	379	91	1,278
August	151	157	253	26	587
September	67	63	69	0	199
October[1]	0	0	0	0	0
November[2]	23	5	14	0	42
December	12	6	12	0	30
Total	1,030	1,130	1,167	498	3,825

[1] Prescribed burn on study plot.
[2] November 15 - new 0.3-m^2 area put on trees.

[5] Mention of trade names is solely to identify study materials and does not constitute endorsement by the U.S. Department of Agriculture.

Beetle response to the paraquat-treated wounds (table 4) increased to a peak about 2 to 3 months after treatment. We think the beetle's aggregation attractant was involved because successful attacks occurred in the wound and on the back side of the trees, but we did not investigate this phenomenon.

STUDY 2 METHODS

The second study was conducted in the same plantation about 1 km from the first study. The objective of this study was to determine whether oleoresin, alone, from either paraquat-treated or untreated wounds, was more or less attractive to Platypus spp. than the actual paraquat-treated wound. On June 3, 1974, 24 trees (four rows of 6 trees each) were treated in the following ways:

1. No wound; no paraquat

2. No wound; no paraquat; gum from treatment 5 placed on bark area where wound would have been made

3. No wound; no paraquat; gum from trees in treatment 6 was placed where wound would have been made

4. No wound; 8 percent paraquat applied daily for 4 days

5. Wound only to one-third of tree circumference (gum exuded used in treatment 2)

6. Wound + 8 percent paraquat (gum exuded used in treatment 3).

Rossing, Tanglefoot application, and insect collection were as in the first experiment.

RESULTS

Ambrosia beetles were found only on trees wounded and treated with paraquat; 403 ambrosia beetles were collected from these trees. The largest numbers were found in July, August, and September (table 5).

The results of this test corroborated the results of the preceding test; ambrosia beetles were attracted to paraquat-treated wounds rather than the fresh oleoresin.

DISCUSSION

In the southwide cooperative research on lightwood induction, many investigators have reported insect problems (Barker 1976; Hertel and Williams 1976; Williams and others 1976). Variations in locality, pine species, wound type, paraquat concentration, wound size, and time of treatment make it difficult to interpret the insect problem. Since the research reported here was directed only at the insect problem, our findings will have to be correlated with information on lightwood production before recommendations can be formulated.

Table 5.--Ambrosia beetles collected each month on 0.3-m^2 areas sprayed with Tree Tanglefoot® around 2.54-cm-wide, $\frac{1}{3}$-circumference wounds sprayed with 2 ml of 8 percent paraquat. Trees were 15-year-old slash pines in Columbia County, Florida. Treatments were applied June 3, 1975

Months	Tree number				Total
	5	6	7	8	
	- - - - - - - - - - - Number - - - - - - - - - - -				
June	0	4	1	3	8
July	49	29	32	57	167
August	22	18	19	9	68
September	10	97	1	0	108
October	0	11	0	0	11
November	12	25	0	4	41
December	0	0	0	0	0
Total	93	184	53	73	403

Important findings are that tree mortality from paraquat treatment was reduced both by decreasing wound size and by lowering the paraquat concentration. Bailey (1976), Crutchfield (1976), and Nix (1976) came to similar conclusions. Wound type (method of wounding), which seemed important in our study and in Crutchfield's (1976), was not an influence in Nix's (1976) study.

The observed reduction in tree mortality when insecticides were applied indicates that the insects are at least contributing to subsequent tree mortality. Death is not solely a phytotoxic reaction. After comparing trees that were treated with paraquat and did not die with those treated with the same paraquat concentration that did die, Nix (1976) concluded that the beetles rather than the paraquat were killing the trees. More definitive experiments are needed to isolate phytotoxicity effects of paraquat from insect-caused tree mortality.

Twenty dead paraquat-treated trees were felled and examined during our studies. No adult beetles emerged from the broods in these trees. The trees evidently acted as traps, and in no case did trees adjoining the study plots come under attack and die.

We noted that wounding trees and applying paraquat in winter reduced the number of trees coming under insect attack and subsequently dying. Crutchfield (1976) and Schnell (1976) had similar findings. We are uncertain, however, about how season of treatment affects lightwood formation. Drew (1976) found that after 3 months, slash pines treated in January with 2 percent paraquat solution had the same level of pitch-soaking enhancement as those trees treated in July. This result is encouraging and should be investigated further.

Studies of ambrosia beetles, P. flavicornis, demonstrated that a wound alone or paraquat applied to undisturbed bark attracted negligible numbers of insects. However, paraquat in contact with exposed xylem, inner bark, and oleoresin produced an attraction to ambrosia beetles that increased with time up to 3 months after treatment. The increase suggests that gradual chemical changes associated with lightwood induction in the tree may affect ambrosia beetle response or that an aggregation pheromone may also be involved in the attraction. These findings cannot be extrapolated to bark beetles and wood-boring beetles that also attack paraquat-treated pines along with the ambrosia beetles. Further research is needed to determine what factors are primarily responsible for specifically attracting Ips spp. and the black turpentine beetle.

This publication reports research involving pesticides. It does not contain recommendations for their use, nor does it imply that the uses discussed here have been registered. All uses of pesticides must be registered by appropriate State and/or Federal agencies before they can be recommended.

CAUTION: Pesticides can be injurious to humans, domestic animals, desirable plants, and fish or other wildlife--if they are not handled or applied properly. Use all pesticides selectively and carefully. Follow recommended practices for the disposal of surplus pesticides and pesticide containers.

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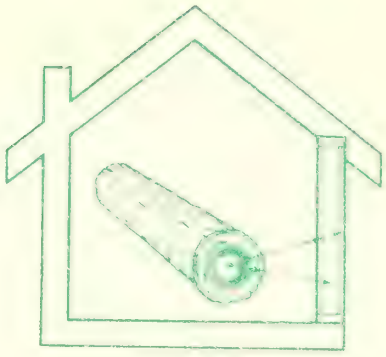

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COM-PLY 5 REPORT

STRENGTH AND STIFFNESS OF COMPOSITE STUDS

COOPERATIVE RESEARCH

STRENGTH AND STIFFNESS OF COMPOSITE STUDS

by

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Cooperative Research by

U.S. Department of Agriculture, Forest Service

Southeastern Forest Experiment Station

and

U.S. Department of Housing and Urban Development

Division of Energy, Building Technology

and Standards

PREFACE

This report is one of a series on the possibilities of producing house framing and structural panels with particleboard cores and veneer facings. These COM-PLY or composite materials were designed to be used interchangeably with conventional lumber and plywood in homes. Research on structural framing is presently limited to COM-PLY studs but will be extended to include larger members such as floor joists.

In 1973, the home-building industry faced a shortage of lumber and plywood and consequent rising prices. Both industry and government recognized that this situation was not a temporary problem, and that long-range plans for better using the Nation's available forest resources would be necessary to solve the problem.

The USDA Forest Service and the U.S. Department of Housing and Urban Development accelerated cooperative research on ways to utilize the whole tree. They concentrated on composite wood products made with particleboard and veneer as a way of using not only more of the tree stem, but also using less desirable trees and a greater variety of tree species than would conventional wood products. The particleboard which comprises a large portion of the COM-PLY stud is made from ground-up wood that comes from forest residues, mill residues, or low-quality timber. Thus, such composites could greatly increase the amount of lumber and plywood available for residential construction, our major use of wood, without eroding the Nation's timber supply.

Research on composite wall framing was performed by the Wood Products Research Unit, Southeastern Forest Experiment Station, Athens, Georgia. The American Plywood Association cooperated in these studies by designing and testing composite panel products that are interchangeable with plywood. Both types of products have been incorporated in demonstration houses.

Included in this series will be reports on structural properties, durability, dimensional stability, strength, and stiffness of composite studs. Other reports will describe the overall project, compare the strength of composite and solid wood studs, suggest performance standards for composite studs, and provide construction details on houses incorporating such studs. Still others will explore the economic feasibility of manufacturing composite studs and panels and estimate the amount and quality of veneer available from southern pines. These reports, called the COM-PLY series, will be available from the Southeastern Forest Experiment Station and the U.S. Department of Housing and Urban Development.

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Charles R. Morschauser, Technical Director
Hubert T. Dudley, Quality Control Director
National Particleboard Association

STRENGTH AND STIFFNESS OF COMPOSITE STUDS

Abstract.--COM-PLY studs made with two plies of 1/7-inch-thick southern pine veneer on each 1-1/2-inch face of a medium-density particleboard core bonded with phenolic resin are strong and stiff enough for use in exterior wall framing of houses. These studs can support a safe design load equal to that of spruce. Holes up to 2-1/2 inches in diameter can be drilled through the stud core if the veneer is not cut. Notching, as for plumbing pipes, causes COM-PLY studs to lose most of their strength and stiffness and is not recommended.

KEYWORDS: COM-PLY lumber, wood veneer, particleboard, wall studs, notched studs.

In a cooperative research project, the USDA Forest Service and the Department of Housing and Urban Development have developed a new composite lumber product. This product, called COM-PLY, is a structural sandwich with a particleboard core between double layers of solid wood veneer (fig. 1). COM-PLY 2 x 4 studs were designed to frame exterior walls in houses. Each stud is about 80 percent particleboard and 20 percent veneer. The particleboard core can be made from forest and mill residues or low-quality timber, thus providing more efficient utilization of our forest resources.

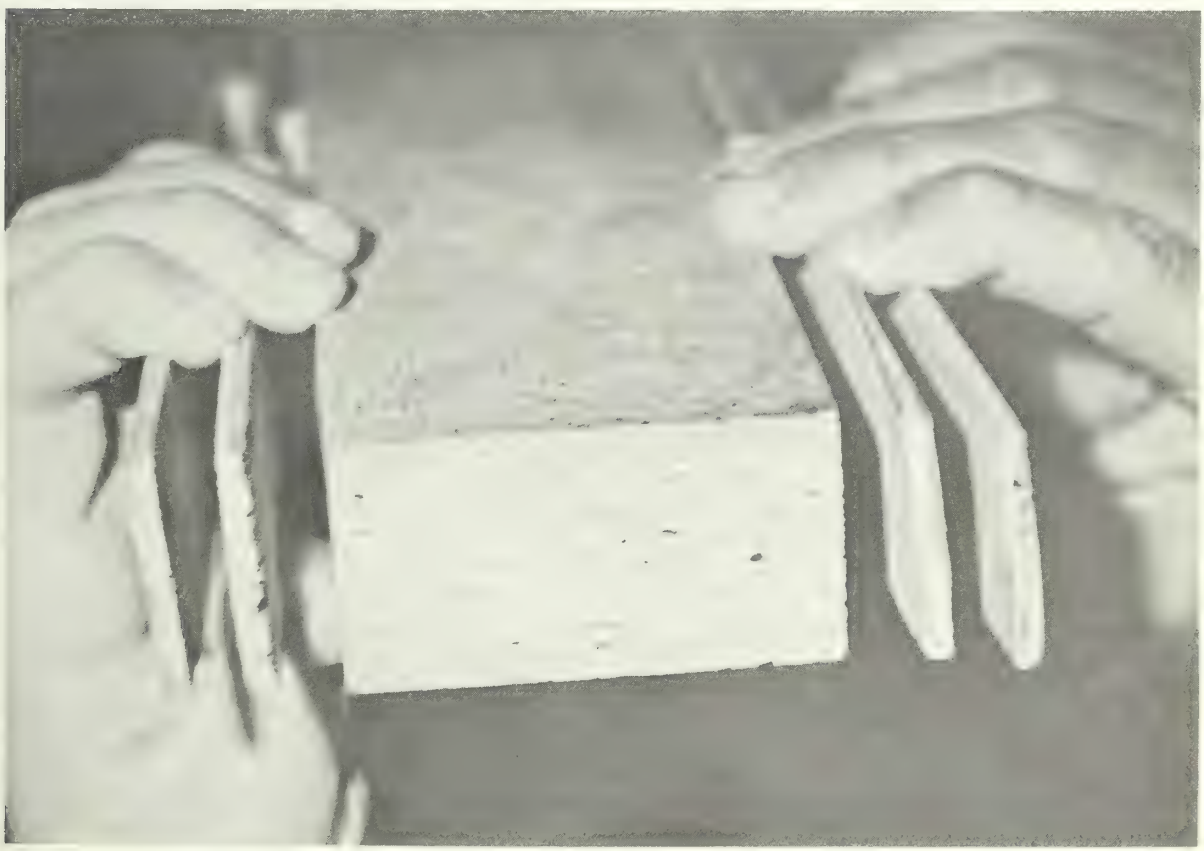

Figure 1.--Components of COM-PLY studs. Note particleboard core between double layers of veneer.

Potential manufacturers, building code officials, builders, and others need to know how COM-PLY and solid wood studs compare in strength and stiffness. Because wall studs are sometimes cut and notched to accommodate wiring and plumbing, it is also important to learn how holes and notches affect the strength and stiffness of the new studs.

This paper reports the strength and stiffness of COM-PLY studs made with various thicknesses and grades of veneer in the laboratory and in pilot manufacture, how this performance compares with that of solid spruce studs, and how the strength and stiffness of composite studs is affected by holes bored in the core and notches through the veneer.

MATERIALS

Researchers tested and evaluated seven groups of studs during this study. Table 1 briefly describes the materials used to make the six groups of composite studs. The seventh test group, stud-grade spruce studs, was randomly selected from stocks of local lumber dealers.

Table 1.--Description of materials used in each group of test studs

Stud group (No.)	Veneer				Particleboard		
	Plies	Thickness	Pine species	Dynamic modulus of elasticity	Binder	Density	Internal bond
		In		Lb/in^2 x 10^6		Lb/ft^3	Lb/in^2
1	2	1/8	Loblolly	1.89	Urea-resin	26	25
2	3	1/8	Loblolly	1.89	Urea-resin	26	25
3	2	1/6	Loblolly	1.81	Urea-resin	26	25
4	2	1/6	Loblolly	1.81	Phenolic	40	75
5	2	1/6	Slash	2.70	Phenolic	40	75
6	2	1/6	Slash	2.70	Phenolic	40	75
7	(1/)	(1/)	(1/)	(1/)	(1/)	(1/)	(1/)

1/ Not applicable. Group 7 consisted of stud-grade spruce studs.

Veneer for stud groups 1 and 2 was 1/8-inch-thick loblolly pine (*Pinus taeda* L.) randomly selected from a test group of veneers at Birmingham Forest Products, Cordova, Alabama. This veneer had an average dynamic modulus of elasticity (MOE) of 1.89 x 10^6 lb/in^2 as determined on stress-wave equipment (Koch and Woodson 1968). Veneer for stud groups 3 and 4 was randomly selected from 1/6-inch-thick loblolly pine supplied by the Southern Forest Experiment Station at Alexandria, Louisiana. This veneer had an average dynamic MOE of 1.81 x 10^6 lb/in^2. Veneer for groups 5 and 6 was 1/6-inch-thick slash pine (*Pinus elliottii* Engelm.) obtained from the U.S. Plywood Mill at Waycross, Georgia. A sample of 88 strips of this veneer had an average dynamic MOE of 2.70 x 10^6 lb/in^2.

Cores for stud groups 1, 2, and 3 consisted of particleboard bonded with urea resin as in door cores. Its average density was 26 lb/ft^3, and internal bond was 25 lb/in^2.

Researchers used a 1-1/2-inch thick phenolic-bonded particleboard core in stud groups 4, 5, and 6. To form this three-layered particleboard, a commercial manufacturer used the air suspension method to separate wood particles by size. These particles were made from southern pine planer shavings, slabs, edgings, and other mill residues. The particleboard had an average density of 40 lb/ft^3, an internal bond of 75 lb/in^2, a modulus of elasticity (in plane of panel) of 300,000 lb/in^2, and a modulus of rupture of 3,400 lb/in^2. Proportion of phenolic-resin binder throughout the three layers was 8 percent.

Figure 2 shows a typical stud made of strips of rotary-cut, southern pine veneer parallel-laminated to the 1-1/2-inch-thick edge of the particleboard core. For the lamination of groups 1 and 2, the veneer strips were 1/8 inch thick, 1-1/2 inches wide, and 96 inches long. Two plies were used on each narrow face of the studs in group 1 and three plies on those in group 2. The particleboard cores were cut 3 inches wide for the studs in group 1 and 2-3/4 inches wide for those in group 2. For groups 3 and 4, the veneer strips were 1/6 inch thick, 1-1/2 inches wide, and 96 inches long. In both groups, two plies were used on each narrow face, and the particleboard cores were cut 2-5/6 inches wide.

Figure 2.--A typical COM-PLY stud after lamination.

All studs in groups 1 through 4 were assembled in the laboratory (fig. 3). For the laminating adhesive, researchers used a phenol-resorcinol resin that cures at room temperature and is typically used in structural glue-laminated timbers. Spread rate of the single gluelines per thousand square feet was 40 pounds for the veneer-to-veneer bond and 100 pounds for the veneer-to-particleboard bond. After a closed assembly time of 15 minutes, researchers applied pressure by placing small numbers of studs in seven, equally spaced bar clamps for a minimum of 24 hours.

Figure 3.--Fabricating COM-PLY studs in the laboratory.

Groups 5 and 6 were randomly selected from a large group of studs made by researchers and workmen at the U.S. Plywood plant at South Boston, Virginia. Facings for these studs had been made at the U.S. Plywood plant at Waycross, Georgia, by parallel-laminating two plies of veneer into 2- by 8-foot sheets. Layup and glue were those regularly used in manufacturing plywood. At South Boston, workmen and researchers cut the veneer into 1-1/2-inch-wide strips and laminated it to the particleboard cores with phenol-resorcinol resin (fig. 4). They used a lumber edge-bonding machine to assemble the studs and apply pressure and heat (Vick, in press). They then stacked the heated studs to allow final curing of the adhesive. From this group, researchers randomly selected 35 studs to be evaluated for strength and stiffness.

PROCEDURES

Researchers tested all seven groups of studs according to "Performance Standards for Composite Studs Used in Exterior Walls" (Blomquist and others 1976). Each stud was tested for strength and stiffness under combined axial compressive end loads and transverse bending loads applied simultaneously. The axial compressive load was applied with a hydraulic cylinder, and the transverse bending load was applied at quarter points with a universal testing machine, as shown in figure 5. In accordance with the formulas in the Performance Standards, the average ultimate test load of each group was adjusted to determine the safe load that studs in the group could carry, and the average deflection at a specified loading was adjusted to determine the maximum deflection that might occur with the given stud design.

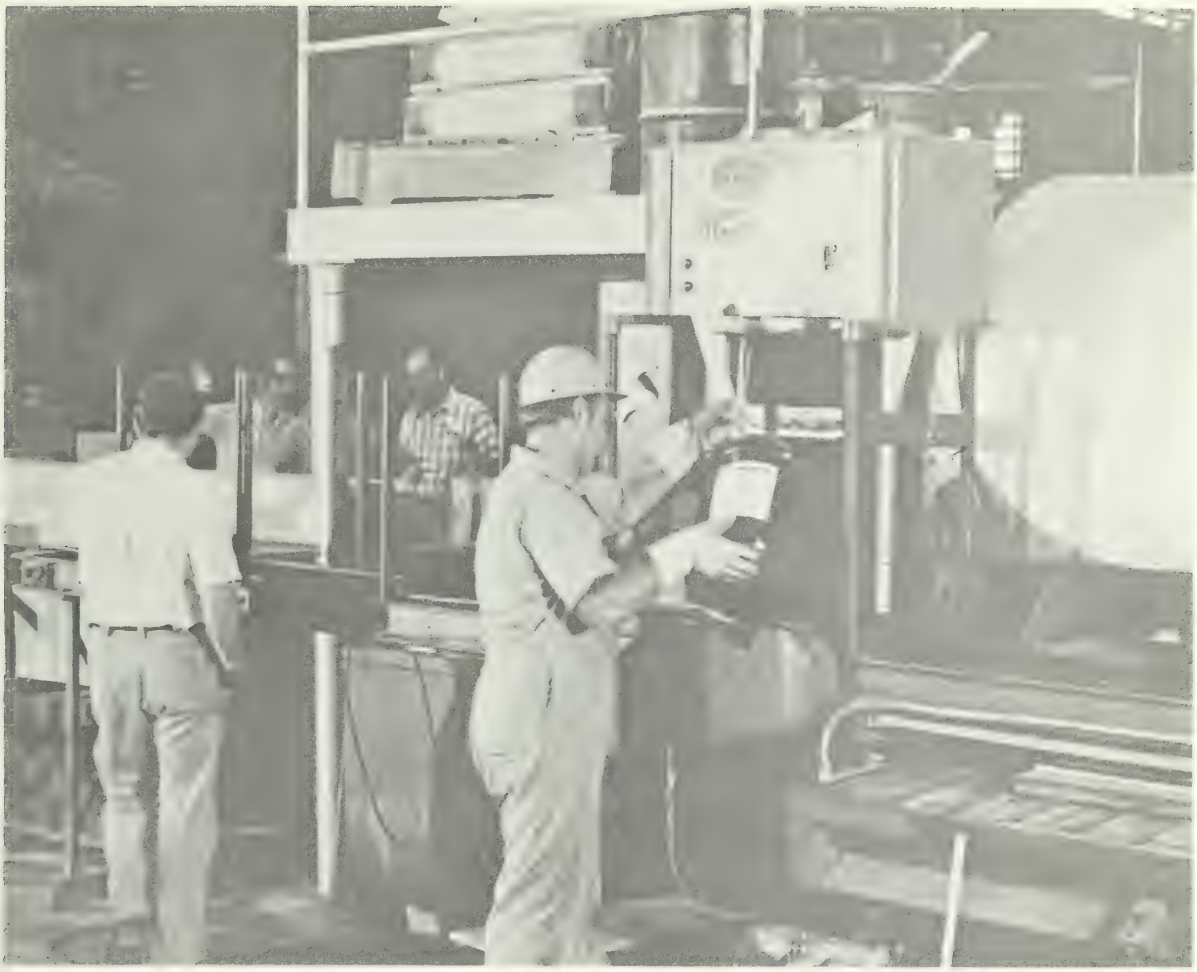

Figure 4.--Fabricating COM-PLY studs in a pilot plant operation.

Before testing group 6, researchers drilled three 1-inch holes through the center of the 3-1/2-inch face of each stud--one hole at midpoint and one 12 inches from each end. After nondestructive testing, researchers found these 1-inch holes did not measurably reduce stiffness of the studs. They then enlarged the holes to 2-1/2 inches in diameter and tested the studs for stiffness and strength. In selected studs, notches were cut through the veneer faces and into the cores before testing (fig. 6).

RESULTS

STRENGTH AND STIFFNESS OF COM-PLY STUDS

Table 2 shows the results of the strength and stiffness tests on the various groups of studs. Stud strengths for each group are shown in terms of average ultimate load, the standard deviation of that load, and the adjusted load. Stiffness values for each group are shown in terms of average deflection under 30 pounds of bending load per linear foot of stud, the standard deviation of that deflection, and the adjusted deflection. All test loads reported in table 2 are lateral bending loads measured while the studs were supporting compressive end loads of 1,190 pounds.

Figure 5.--COM-PLY stud under combined loading in a universal testing machine.

Researchers used stud groups 1, 2, and 3 to determine how the thickness and number of veneers affected strength and stiffness. The results showed that, when adjusted loads were calculated, two plies of 1/6-inch-thick veneer glued to each side of the particleboard core (group 3) were as strong as three plies of 1/8-inch-thick veneer (group 2). The studs with three plies of 1/8-inch-thick veneer (group 2) had a greater standard deviation in strength than all other COM-PLY groups except 5.

For a COM-PLY stud to meet the Performance Standard for strength and stiffness, its adjusted bending load must be 40 pounds or more per linear foot of stud and the adjusted deflection must not exceed 0.412 inch under a bending load of 30 pounds per linear foot. The results showed that studs with two plies of 1/8-inch-thick veneer (group 1) did not meet these minimum requirements, whereas those with two plies of 1/6-inch-thick veneer (group 3) had more than adequate strength but did not quite pass the stiffness requirement. However, studs in group 4 with the same number and thickness of veneer plies but stronger cores passed both the stiffness and strength requirements. Consequently, researchers believe the ideal dimensions for southern pine veneers in COM-PLY studs would be two plies, each 1/7 inch thick.

Studs in group 5 were exceptionally strong, primarily because the slash pine veneer used in that particular group had an average MOE of 2.7×10^6 lb/in^2. This is a rather high MOE for slash pine.

Groups 3 and 4 had different kinds of particleboard cores. Group 4 had a phenolic-bonded core with a density of 40 lb/ft^3, and group 3 had a urea-resin-bonded core with a density of 26 lb/ft^3. As previously noted, the studs in group 3 failed to meet the stiffness requirement. The studs in group 4, however, were strong and stiff enough to use in wall framing and more accurately represented a well-designed stud that a manufacturer might produce commercially.

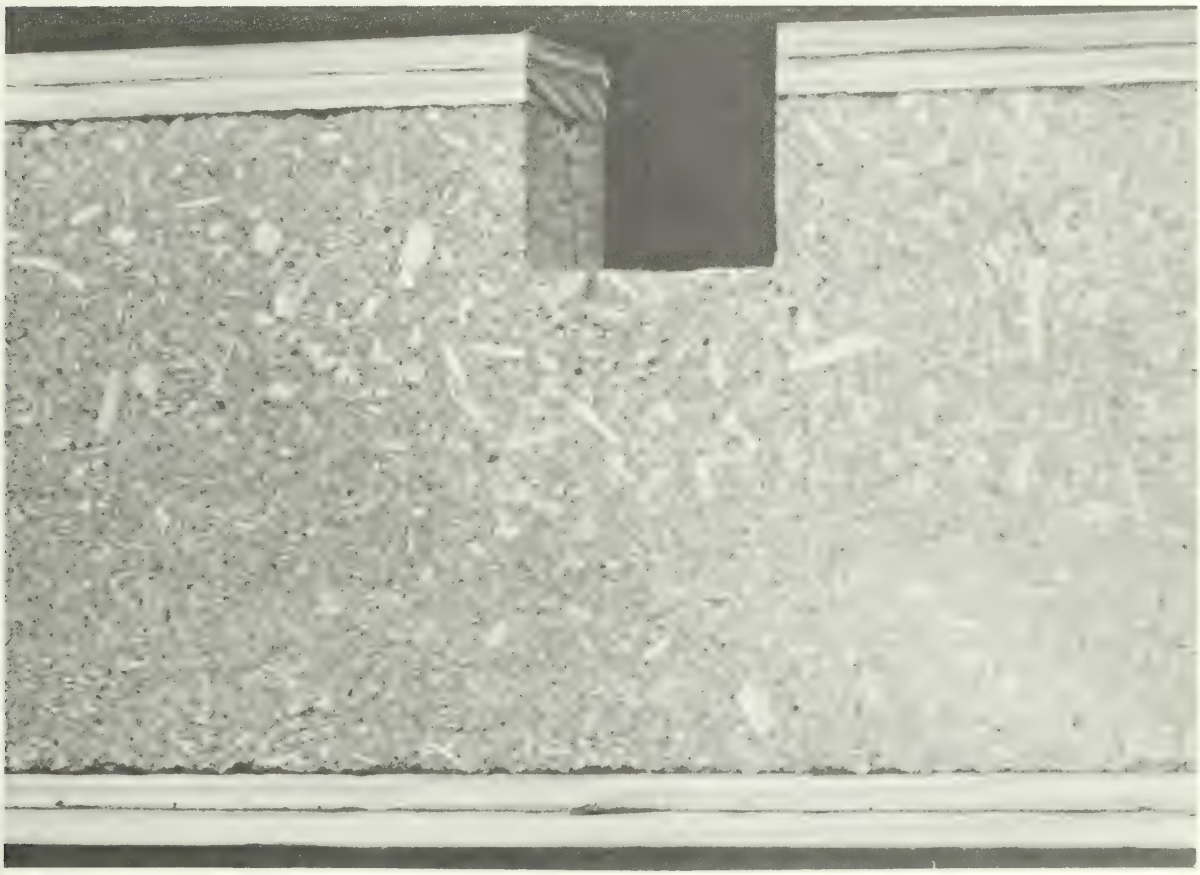

Figure 6.--COM-PLY stud after notching.

COMPARATIVE STRENGTH AND STIFFNESS OF COMPOSITE AND SPRUCE STUDS

The spruce studs (group 7) had a higher average ultimate load capacity than any group of COM-PLY studs in this study, but their standard deviation in ultimate load strengths was more than twice that of the COM-PLY studs (table 2). Because the COM-PLY studs had less variation in average ultimate load strengths, their adjusted loads were closer to that of spruce than were their ultimate loads.

Spruce studs had the lowest average deflection under a 30-pound lateral load and the lowest adjusted deflection. However, COM-PLY groups 2, 4, 5, and 6 passed the stiffness requirement set forth in the Performance Standard.

EFFECT OF BORING HOLES AND NOTCHING STUDS

Because groups 5 and 6 were made with essentially the same materials, group 5 served as a control in determining the effect of boring 2-1/2-inch holes through the cores of the studs in group 6. If we assume that groups 5 and 6 had essentially equal strength and stiffness, then the presence of holes reduced the

adjusted load of group 6 from 73.2 to 43.0 lb/lin ft, or about 41 percent (table 2). The holes reduced stiffness by only a small amount: the adjusted deflection of group 6 increased from 0.288 to 0.300 inch, or about 4 percent. Thus, after boring 2-1/2-inch holes through the stud cores, this particular group of studs still met the Performance Standard for strength and stiffness.

Notching through the veneer faces reduced the strength and stiffness of the studs so that they failed under a 1,190-pound end load before any lateral load was applied.

Table 2.--Results of strength and stiffness tests on composite and solid spruce studs[1/]

Stud group (No.)	Studs tested	Ultimate bending load		Adjusted bending load[2/]	Deflection under bending load of 30 lb/lin ft		Adjusted deflection[3/]
		Average ($\bar{w}$)	Standard deviation (S)	(W)	Average ($\bar{d}$)	Standard deviation (S)	(D)
	No.	Lb/lin ft			In		
1	15	65.0	10.3	26.2	0.450	0.049	0.472
2	15	114.2	18.2	45.2	.301	.036	.311
3	30	104.1	15.0	45.2	.399	.057	.416
4	30	115.2	13.7	57.0	.321	.050	.346
5	20	154.2	18.6	73.2	.269	.050	.288
6	15	100.4	15.9	43.0	.284	.037	.300
7	61	193.9	60.8	49.8	.231	.048	.241

1/ Symbols in the boxheads refer to values in the formulas for determining acceptable strength and stiffness (Blomquist and others 1976).

2/ To be acceptable, the adjusted bending load must be 40 pounds or more per linear foot of stud.

3/ To be acceptable, the adjusted average deflection must be 0.412 inch or less.

CONCLUSIONS

Various species of southern pine veneer can be used in designing and manufacturing composite studs that are strong and stiff enough for use in wall framing. The ideal amount of veneer for COM-PLY studs would be two plies, each 1/7 inch thick. This veneer should be glued to each 1-1/2-inch face of a phenolic-bonded particleboard core with a density of about 40 lb/ft^3. When used in wall framing, such studs can support a safe design load equal to that of spruce studs. Although they are not as stiff as spruce studs, these COM-PLY studs will meet the Performance Standard for stiffness (Blomquist and others 1976).

Holes up to 2-1/2 inches in diameter can be drilled through the stud core if the veneer on the faces is not cut. However, notching, as for plumbing pipes, causes COM-PLY studs to lose almost all their strength and stiffness and is not recommended. The faces of each stud, therefore, should be marked with a warning against notching through the veneer. Accidental cutting or notching of a limited

number of studs could perhaps be corrected by using splice or gusset plates to restore some of the strength and stiffness. However, we did not test reinforcement methods for notched studs and cannot make recommendations on their effectiveness. Workmanship becomes an important factor when splice or gusset plates and other repair methods are used. Therefore, reinforcement methods for notched studs should be approved by local building inspectors.

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COM-PLY studs made with two plies of 1/7-inch-thick southern pine veneer on each 1½-inch face of a medium-density particleboard core bonded with phenolic resin are strong and stiff enough for use in exterior wall framing of houses. These studs can support a safe design load equal to that of spruce. Holes up to 2½ inches in diameter can be drilled through the stud core if the veneer is not cut. Notching, as for plumbing pipes, causes COM-PLY studs to lose most of their strength and stiffness and is not recommended.

KEYWORDS: COM-PLY lumber, wood veneer, particleboard, wall studs, notched studs.

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COM-PLY 6 REPORT

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ADHESIVES FOR COM-PLY STUDS

Abstract.--Several adhesives and bonding techniques have been initially evaluated for use in factory lamination of veneer strips to particleboard cores in COM-PLY studs. Phenolic-base resin adhesives, whether modified with resorcinol or not, produced strong, durable bonds and showed promise for reducing costs. Flat platens, preheated wood, and high-frequency curing merit more investigation as ways to speed curing of such adhesives in COM-PLY studs.

KEYWORDS: Composite lumber, phenolic adhesive, phenol-resorcinol adhesive, resorcinol-modified phenolic adhesive, melamine-urea adhesive, performance requirements, bonding techniques.

Researchers of the USDA Forest Service, cooperating with the Department of Housing and Urban Development and leading manufacturers of forest products, have developed a new composite building product called the COM-PLY stud. Designed as a way to utilize entire logs for structural lumber, COM-PLY studs consist of layers of parallel-grain veneer bonded to each edge of a particleboard core to form a composite sandwich construction (fig. 1). Veneer from the outer portion of the log strengthens and stiffens the edges of the studs; the inner portion of the log is ground up to make the particleboard core. COM-PLY studs are intended as economical, practical substitutes for conventional 2 x 4 studs in wall framing of houses.

One important aspect of the COM-PLY program was the selection of adhesives and bonding techniques for laminating veneer and particleboard into studs. Researchers wanted to find strong, durable, low-cost adhesives that could be cured quickly with standard production equipment. This search led them to devise tests and special performance requirements for particleboard-to-veneer bonds, which had never before been used to support structural loads in construction.

This paper describes the selection of suitable adhesives and evaluation of the bonds produced; the working characteristics of each adhesive in terms of spreading, assembly, and curing; and efforts at finding faster methods of curing. Specific recommendations are made for further testing of the most promising adhesives and techniques for fabricating COM-PLY studs.

CRITERIA FOR SELECTING AND EVALUATING ADHESIVES

SELECTING ADHESIVES FOR STUDY

Our choice of commercial adhesives for laminating veneer to particleboard was limited, particularly by the requirements for high strength and durability of bonds. To ensure that COM-PLY studs would be durable enough for constructing houses, we needed adhesive bonds that could withstand short-term, but severe, exterior exposure. Thermosetting adhesives (those undergoing chemical reaction leading to an infusible state) generally meet these requirements. A possible exception to this generalization is the melamine-urea blends. Blomquist and Olson (1955) and Gillespie and River (1975) have shown that bonds made with these adhesives lose strength after prolonged outdoor weathering or accelerated aging.

Figure 1.--Cross section of a conventional stud (left) and a COM-PLY stud (right).

Thermosetting adhesives are petro-chemicals, and their costs have risen sharply because of world-wide shortages of petroleum. Thus, adhesives will constitute a significant part of the total costs of manufacturing COM-PLY studs. The thermosetting adhesives listed below are in descending order of costs per pound of all components when purchased in bulk quantities. Prices are approximate as of July 1974:

Adhesive types	Cents per pound
Resorcinol-formaldehyde	65-70
Phenol-resorcinol-formaldehyde	38-43
Melamine-formaldehyde	34-35
Melamine-urea-formaldehyde	31-32
Resorcinol-modified phenol-formaldehyde	23-26
Phenol-formaldehyde	15-16

Resorcinol-formaldehyde and phenol-resorcinol, the most expensive adhesives and the most reactive, cure at room temperature within hours. However, they require additional heat for rapid, production-line curing. The first of these adhesives was excluded from consideration because of its high cost, and even the second would be uneconomical at high spread rates (Koenigshof 1975). The remaining adhesives are less expensive, but they are also less reactive and can be cured only at high temperatures. The cheapest adhesive, phenol-formaldehyde, is the least reactive and must be cured at 250° F or above for considerable time. Generally, curing an adhesive of lower reactivity costs more for equipment and energy.

When used to bond thin materials such as plywood, the less reactive phenolics can be cured efficiently at 250° to 350° F within a few minutes. Therefore, if the two-ply veneers for COM-PLY studs are laminated before the studs are fabricated, phenolic hot-press adhesives will undoubtedly be the logical choice. The technology for using them is well known in plywood manufacturing. The major problems, however, are how best to apply heat to the bondline between the veneer laminate and particleboard core and how to cure a low-cost phenolic adhesive within a reasonable time. Therefore, only particleboard-to-veneer bonds were considered in evaluating thermosetting adhesives for laminating COM-PLY studs. The target curing time in these studies was 5 minutes.

MINIMUM PERFORMANCE REQUIREMENTS

Studs are normally used inside a wall, where sheathing protects them from weathering. Occasionally, though, studs are exposed to water and to extremes of temperature and humidity during shipment and storage, at the building site, or during service (fig. 2). Minimum performance criteria based on bending tests and accelerated aging were therefore established to ensure that COM-PLY studs can withstand at least 1 year of unprotected weathering without serious losses in strength and stiffness (Duff, in press). We also tested studs by subjecting them to 1 year of outdoor weathering. Neither of these tests, however, is fast enough for use in quality control of the bondlines.

We therefore decided to establish minimum performance requirements and rapid tests for evaluating the durability of the particleboard-to-veneer bonds. No standards existed for evaluating composite materials during short periods of weathering. Consequently, we either had to choose requirements and tests arbitrarily or adopt those already set up for solid-wood products in exterior use. Such test methods and requirements would be used only to control the quality of bondlines during the manufacturing process, not to evaluate the strength and long-term durability of the adhesives. The latter were already well known from many years of laboratory tests and actual use.

The adhesive bond between the veneer and particleboard core was evaluated in terms of dry shear strength, related wood failure, and resistance to delamination. These tests were considered important in view of the different stresses that might be applied when studs are loaded, and perhaps undergo weathering, during service. The test for dry shear strength measured the bondline's ability to withstand combined axial and bending loads. Percentage of wood failure, or the measured area of ruptured wood fibers visible in a sheared joint, was another measure of bondline integrity. A high percentage of wood failure--70 percent or more--shows that a joint is virtually as strong as the wood being bonded.

Procedures for testing dry shear strength and wood failure were those specified in ASTM Method D 1037-72a (ASTM 1975), except for the following: The width of block-shear specimens (fig. 3, left) was changed from 2 inches to 1-1/2 inches (the width of COM-PLY studs), and the length of the shear area was changed from

1-1/2 inches to 2 inches in order to maintain the specified shear area of 3 in^2. Also, the rate of loading was increased from 0.024 to 0.10 inch per minute in order to reduce testing time.

Figure 2.--Stack of snow-covered COM-PLY studs at a building site. Note studs already in place as wall framing.

The minimum acceptable average for dry shear strength of the particleboard-to-veneer bondlines was set at 500 lb/in^2. This value was approximately 3-1/2 times the calculated maximum horizontal shear stress that developed when an exceptionally strong and stiff stud failed under combined axial and bending load.

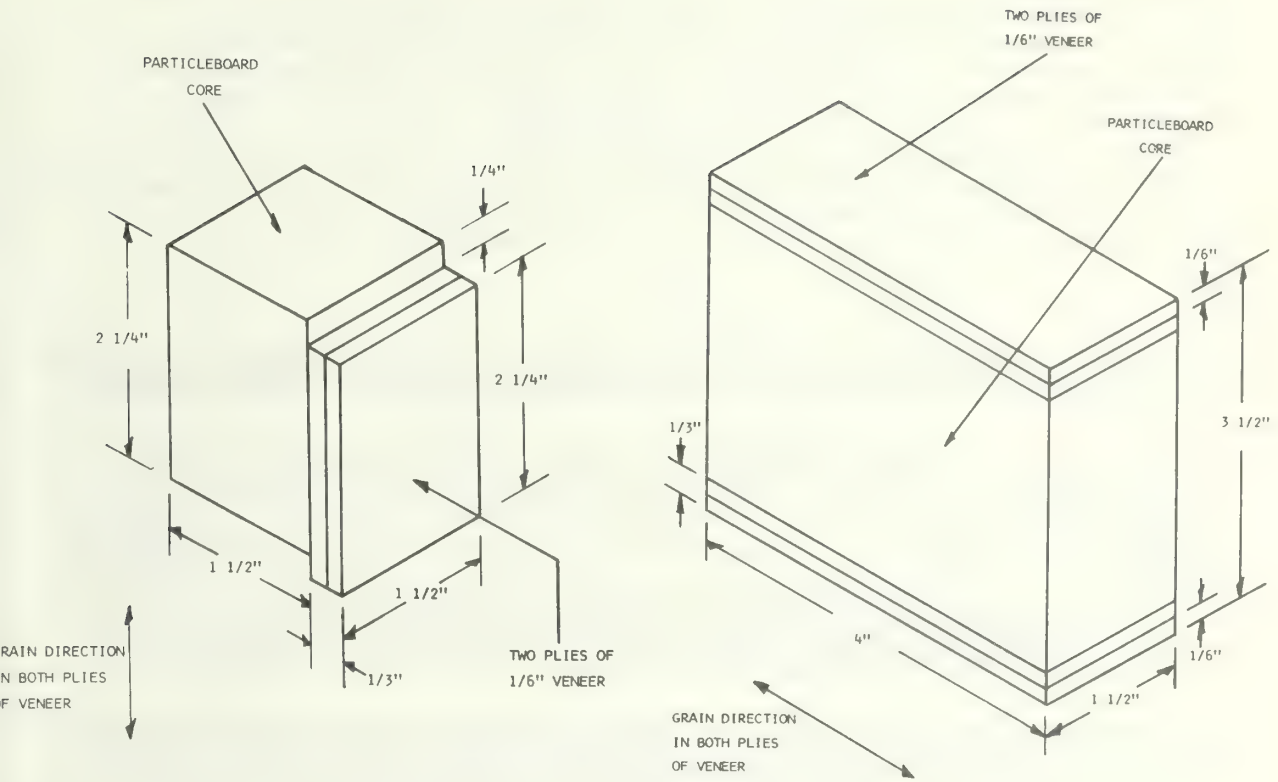

Figure 3.--Configuration and dimensions of block-shear specimen for compression loading (left) and cross section of stud for delamination test (right).

The minimum requirement for wood failure was set at 80 percent for adhesive joints prepared in the laboratory. Seventy-percent wood failure was the minimum allowable for joints in studs made on a production line. Standard AITC 201-63 (AITC 1963) for softwood lumber laminations in exterior use makes these distinctions between wood failure requirements according to how and where the bondlines are made.

We considered resistance to delamination the most dependable indicator of a stud's performance in service. Even though a joint may have shear strength greater than the design load, it can delaminate under severe stresses from swelling and shrinking during weathering, thereby reducing the strength and stiffness of the entire stud. Resistance to delamination was tested by an accelerated aging process that subjected bondlines of stud specimens (fig. 3, right) to alternate cycles of vacuum-pressure soaking and drying. Five percent was the allowable delamination on end-grain surfaces of specimens made in the laboratory. Ten percent was allowed in studs made on a production line. These delamination requirements and testing procedures were those specified in AITC 201-63 (AITC 1963). Two cycles of soaking were used, instead of the three required for exterior lumber laminations.

PHENOL-RESORCINOL-FORMALDEHYDE ADHESIVE

MATERIALS AND METHODS

For the pilot production of COM-PLY studs in a factory, a phenol-resorcinol adhesive was selected for laminating the veneer strips to the particleboard cores, as described by Vick (in press). It was selected because it is the cheapest

commercial adhesive that can provide the required strength and durability of bonds and yet be cured quickly. Before this adhesive was used at the factory, we tested it on short sections of COM-PLY studs in the laboratory. There we simulated conditions of factory assembly and curing to determine the optimum spread rate, method of spread, assembly time, and curing time for this particular adhesive.

A laboratory hot-press simulated the operating conditions of the 20-foot, continuous edge-bonding machine used for curing at the factory. The bondlines between veneer and core were oriented vertically to the platens of the hot-press, just as the bondlines of COM-PLY studs would be in the edge-bonding machine (fig. 4).

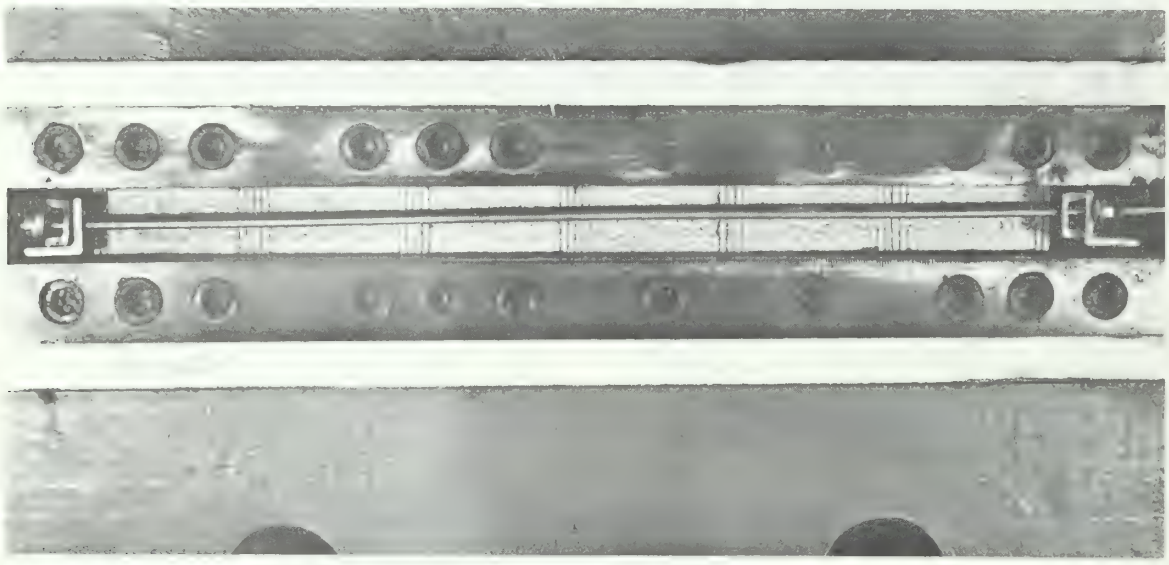

Figure 4.--Laboratory hot-press used to simulate edge-bonding machine. Bondlines are vertical to platens.

In the hot-press, the bondlines were cured at 350° F for 5 minutes--the maximum curing time available with a 20-foot, continuous edge-bonder. These conditions did not completely cure the adhesive throughout the 1-1/2-inch thickness of the stud. According to the manufacturer's test data, the curing cycle for this adhesive is about 2 minutes at 180° F. Thermocouples inserted in the test studs during hot-pressing showed that temperatures after 5 minutes of curing reached 340° at the surface, 210° at a depth of 1/4 inch from each platen, and 130° at a depth of 3/4 inch (fig. 5). These data indicate that the adhesive would cure at least 1/4 inch from each platen within 5 minutes because the temperature at that depth would have remained at 180° or more for about 2-1/2 minutes. This curing at the edges would hold the veneer and core together until the bondlines at the center of the stud could completely cure from residual heat during overnight hot-stacking.

WORKING CHARACTERISTICS

The results of the laboratory tests on phenol-resorcinol adhesive are shown in table 1. The minimum conditions resulting in bonds with acceptable shear strength, wood failure, and delamination were single-spreads of adhesive on particleboard at a rate of 80 lb/Mft^2 (pounds per thousand square feet) with a maximum closed assembly time of 10 minutes (test 1). Any increase in closed assembly

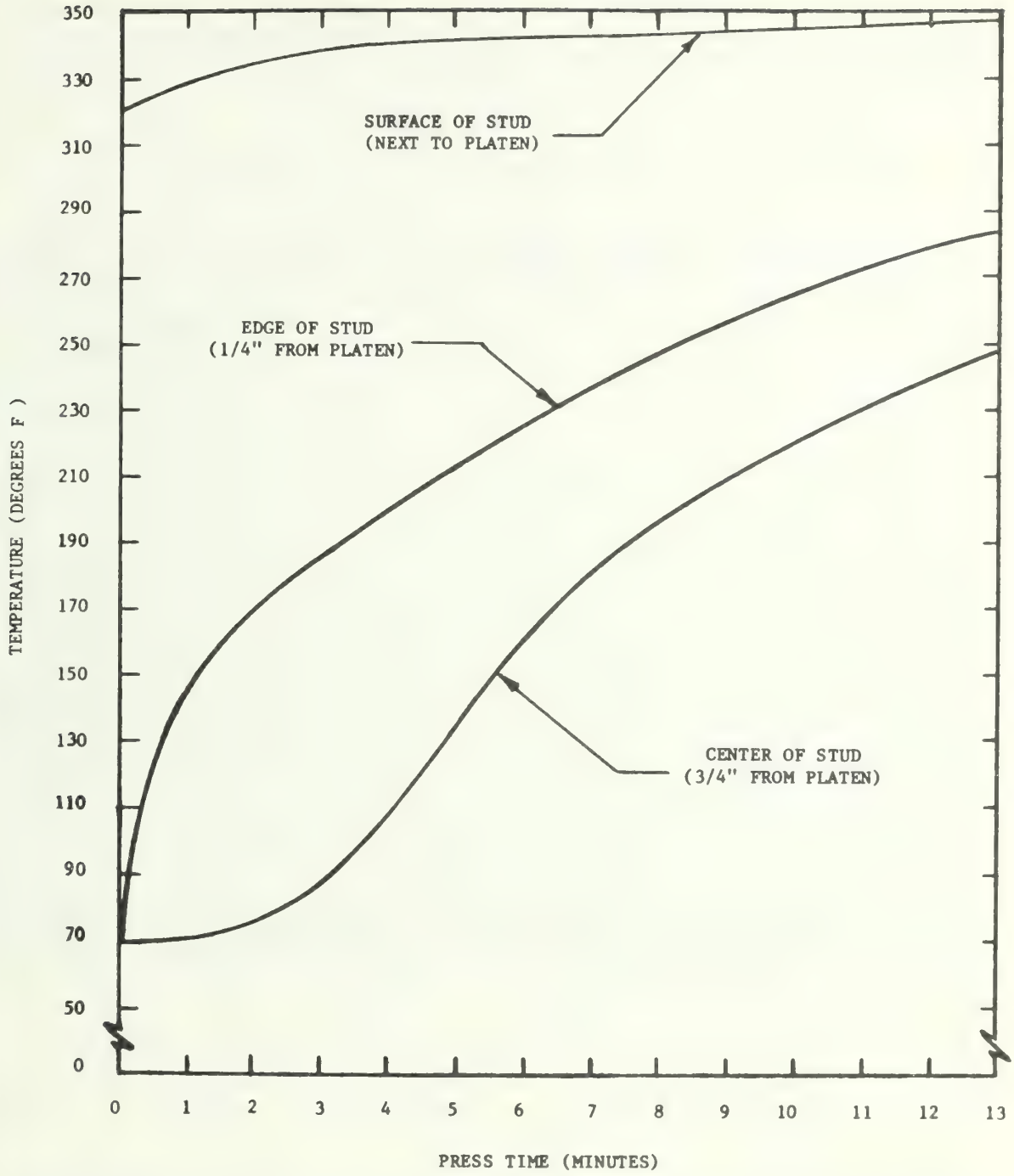

Figure 5.--Rate of temperature rise in bondlines at various locations in COM-PLY studs during hot-pressing.

time at this rate of single-spread resulted in unsatisfactory bonds (test 2). Double-spreading on both the particleboard and the veneer at a combined rate of 80 lb/Mft^2 improved bond quality, particularly in terms of wood failure and resistance to delamination (tests 3 and 4). Increasing the single-spread rate from 80 to 100 lb/Mft^2 on particleboard also resulted in considerable improvement in

bonds (test 5). But again there was some deterioration in bond quality as closed assembly time was increased (test 6). The advantage of double-spreading was apparent in tests 7 and 8, where shear strength and wood failure increased further after closed assembly times of 10 and 20 minutes.

Table 1.--Shear strength, wood failure, and delamination of particleboard-to-veneer bonds made with phenol-resorcinol adhesive at various spread rates and assembly times

Test (No.)	Adhesive spread rate		Maximum closed assembly time	Mean shear strength[1/]	Mean wood failure[1/]	Delamination[2/]
	Particleboard	Veneer				
	-----Lb/Mft^2-----		Min	Lb/in^2	-----Percent-----	
1	80	0	10	577	80	3.0
2	80	0	20	487	66	13.5
3	50	30	10	592	85	0
4	50	30	20	670	76	1.3
5	100	0	10	660	86	0
6	100	0	20	598	82	3.2
7	60	40	10	724	92	2.0
8	60	40	20	656	91	0
9	120	0	10	692	91	0.3
10	120	0	20	777	86	0.8
11	60	60	10	624	93	0
12	60	60	20	659	96	0
13	140	0	10	790	71	3.7
14	140	0	20	659	89	0
15	80	60	10	631	95	0
16	80	60	20	637	83	0

1/ Mean values based on 20 block-shear specimens.

2/ Mean values based on five stud specimens.

In the remaining tests, combinations of single- and double-spreading, increased spread rates, and adjusted assembly times did not result in significant improvements in overall bond quality. The results of test 13 were erratic. The high shear strength and low wood failure in this test are typical of joints made with high-density veneer that contains thick, wide bands of summerwood in the bonding face. The strength of such bonds to summerwood usually are considerably stronger than bonds to springwood. When these joints are sheared, though, wood failure only develops in the plane of the weaker, adjacent springwood rather than the stronger, higher-density summerwood.

The results of the tests shown in table 1 were the basis for using phenol-resorcinol adhesive in the factory lamination. Because spread would undoubtedly vary during pilot manufacturing, the adhesive was spread on each edge of the particleboard core at a rate of 100 lb/Mft^2, even though spread rates of 80 lb/Mft^2 were satisfactory in the tests. The veneer was left uncoated to simplify stud assembly and to reduce manpower and equipment required. The allowable closed assembly time was 10 minutes.

The heavy spreads of adhesive were necessary because of the rough surfaces on the sawn edges of particleboard to which the veneer was bonded (fig. 6). These core edges were filled with cavities created when particles were torn out during the sawcut. Thus, only about 60 percent of the core edges actually made close

contact with the veneer. To achieve high wood failure on these particleboard edges, it was necessary to cover all particles completely as well as provide ample adhesive for transfer to the opposite veneer faces. If particles at the bottoms of cavities were not coated with adhesive as were those on the surface, then only the surface particles in close contact with veneer would tear out, and low wood failure would result. The heavy adhesive spreads of 100 lb/Mft^2 could be reduced perhaps 30 to 40 percent if a smooth particleboard edge could be produced. Such edges would require changes in the sizes and shapes of particles used in the board.

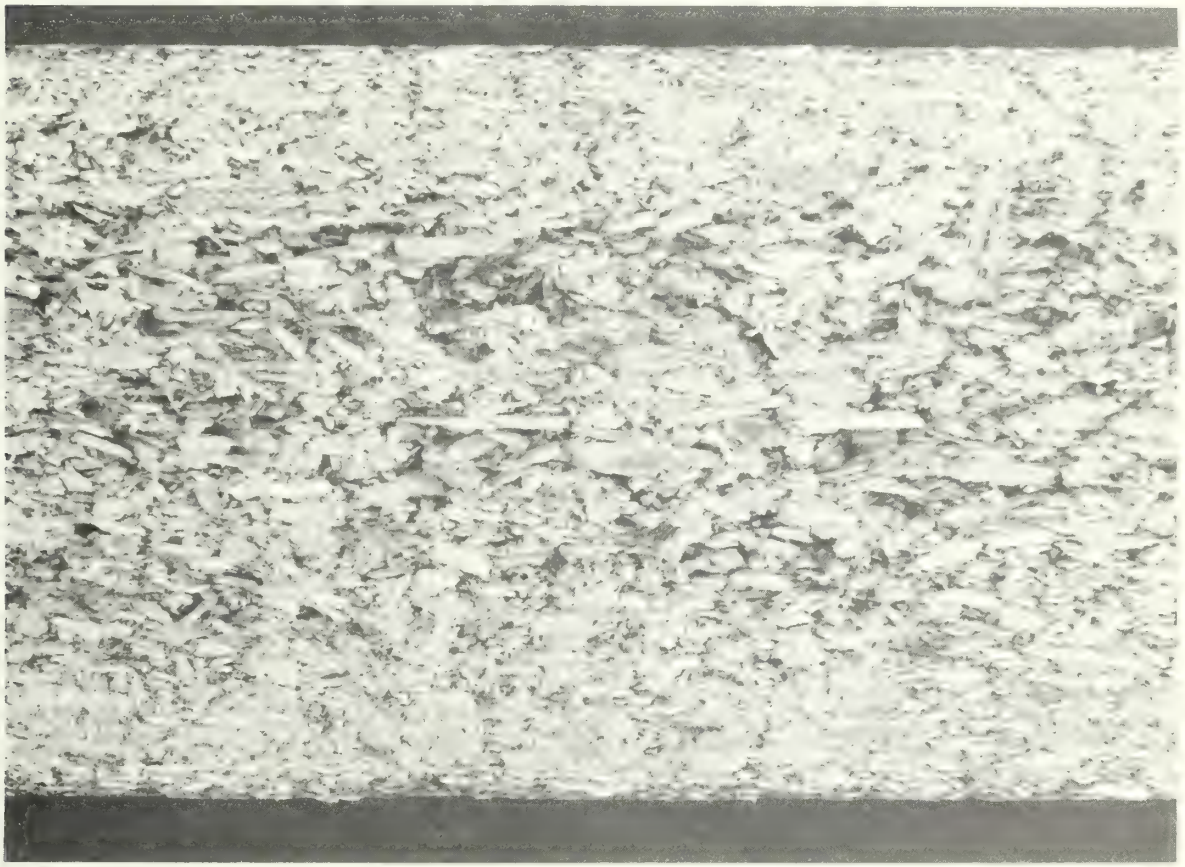

Figure 6.--Rough edge of a particleboard core.

WATER DILUTION OF PHENOL-RESORCINOL-FORMALDEHYDE ADHESIVE

MATERIALS AND METHODS

One possibility for reducing the costs of adhesives was to dilute conventional phenol-resorcinol resin with water and then convert the diluted mixture to its original consistency by adding filler. Accordingly, we prepared two water-diluted formulations for testing. For the first, 50 parts of water by weight were added to 100 parts of resin to make a 67 percent resin solution. Then 26 parts of walnut-shell flour were added to the resin solution along with the usual 20 parts of hardener, which already contained about 50 percent walnut-shell flour. With this formulation, a given weight of resin made about 63 percent more adhesive mixture than it would without dilution. For the second formulation, we added 25 parts of water to 100 parts of resin to make an 80 percent resin solution. Fifteen parts of filler and 20 parts of hardener were then added to the solution. With this second formulation, a given weight of resin extended the adhesive mixture by 33 percent.

Adhesive bonds prepared with these two formulations were tested at various rates and methods of spread. Assembly times were restricted to 10 minutes because earlier tests had shown that longer assembly times resulted in marginal bonds at best.

WORKING CHARACTERISTICS

The results of tests on the two water dilutions of phenol-resorcinol adhesive are shown in table 2. The first (the 67 percent resin solution) did not develop satisfactory bonds. None of the joints could meet the wood failure requirement of 80 percent, although joints that were double-spread at rates of 100, 120, and 140 lb/Mft^2 did meet the minimum requirement of 500 lb/in^2 for shear strength and the maximum allowable delamination of 5 percent (tests 1-3).

Table 2.--Shear strength, wood failure, and delamination of particleboard-to-veneer bonds made with two water dilutions of phenol-resorcinol adhesive at various spread rates

Test (No.)	Adhesive spread rate		Mean shear strength[1/]	Mean wood failure[1/]	Delamination[2/]
	Particleboard	Veneer			
	---Lb/Mft^2---		Lb/in^2	-----Percent-----	
			67 PERCENT RESIN SOLUTION		
1	60	40	731	71	1.9
2	60	60	801	65	1.6
3	80	60	654	56	0
4	140	0	651	43	8.1
5	140[3/]	0	765	68	2.0
			80 PERCENT RESIN SOLUTION		
6	80	0	460	78	1.8
7	50	30	519	75	1.5
8	100	0	580	92	2.2
9	60	40	614	82	.4

1/ Mean values based on 20 block-shear specimens.
2/ Mean values based on five stud specimens.
3/ Adhesive contained 10 parts per hundred more walnut-shell flour than other mixtures.

The second formulation (the 80 percent resin solution) produced bonds of adequate quality when we used single- and double-spreads of 100 lb/Mft^2 (tests 8 and 9). Lower spread rates proved inadequate. The 10-minute closed assembly time was sufficient with this formulation. The adhesive was cured by hot-pressing with bondlines vertical to platens for 5 minutes at 350° F and then hot-stacking overnight, the same curing schedule used with conventional phenol-resorcinol.

This work with diluted phenol-resorcinol resin adhesive was beneficial in two ways. First, we found a formulation that extends the coverage of a conventional

phenol-resorcinol by 33 percent. Second, we found that a content of resin solids near 30 percent instead of the conventional formulation of 45 percent will produce strong bonds in COM-PLY studs. Such a reduction in solid content would amount to a 20 to 25 percent savings in adhesive costs.

MODIFIED PHENOL-FORMALDEHYDE ADHESIVE

MATERIALS AND METHODS

Phenol-formaldehyde adhesive is well known for its ability to form strong, durable bonds in plywood and particleboard at a reasonable cost. This adhesive is used almost exclusively in the commercial manufacture of exterior plywood. When a maximum of durability is required, it is also the preferred binder for particleboard. Because most problems of production technology with this adhesive have been solved, it probably will be used to manufacture particleboard for COM-PLY studs. A phenolic adhesive especially formulated for southern pine veneers will also be used to laminate the veneers of COM-PLY studs if this laminating process is done separately from the assembly of the studs.

However, laboratory tests have shown that conventional phenolic formulations for southern pine veneers do not produce satisfactory bonds between veneer and particleboard. Such bonds were unsatisfactory even when a catalyst was added to hasten curing time and variations were made in the normally recommended assembly times (open and closed), temperature and moisture content of the wood members, and rates and methods of spread. It was possible to obtain shear strengths over 600 lb/in^2 with a conventional formulation by extending closed assembly time to 20 minutes on dry materials (about 5 percent moisture content). However, strong bonds did not develop on materials at 9 to 12 percent moisture content. We could not produce acceptable levels of wood failure under any conditions. These unsuccessful attempts repeatedly indicated that the adhesive was overpenetrating the particleboard core during hot-pressing.

The problem of overpenetration was solved by modifying the phenolic adhesive so that it contained little or no added water and a high proportion of phenolic resin (80 to 85 percent instead of the conventional 65 percent). Assembly times were lengthened to allow moisture losses. The standard phenolic mixture and the two most successful modifications are described below:

Ingredients	Conventional formulation	Modified formulation: FSL-1	FSL-2
	(Units of weight)	(Units of weight)	
Phenolic resin	140.0	180.0	140.0
Water	37.5	10.0	0
Co-Cob™ (filler)[1/]	20.0	13.5	20.0
Wheat flour (filler)	8.5	7.5	0
Caustic (50 percent NaOH)	8.5	9.0	7.0

1/ Mention of commercial products in this paper does not constitute endorsement by USDA to the exclusion of other products that may be suitable.

Both of these modified phenolics solved the penetration problem. We did not test for minimum spread rates, methods of spread, minimum curing times, and tolerances to ranges of wood moisture content. Such factors can be determined once a practical method is found for production curing of phenolic resins.

In all but one test with these modified phenolics, the heating platens of the hot-press were in direct contact with the faces of the veneer (fig. 7). In all tests, the temperature of the platens was about 350° F and pressure was about 150 lb/in^2. Adhesive joints were kept in the hot-press almost long enough to cure them completely--about 10 minutes. Curing time for these joints should be about the same as for 5/8-inch-thick softwood plywood made with phenolic adhesive.

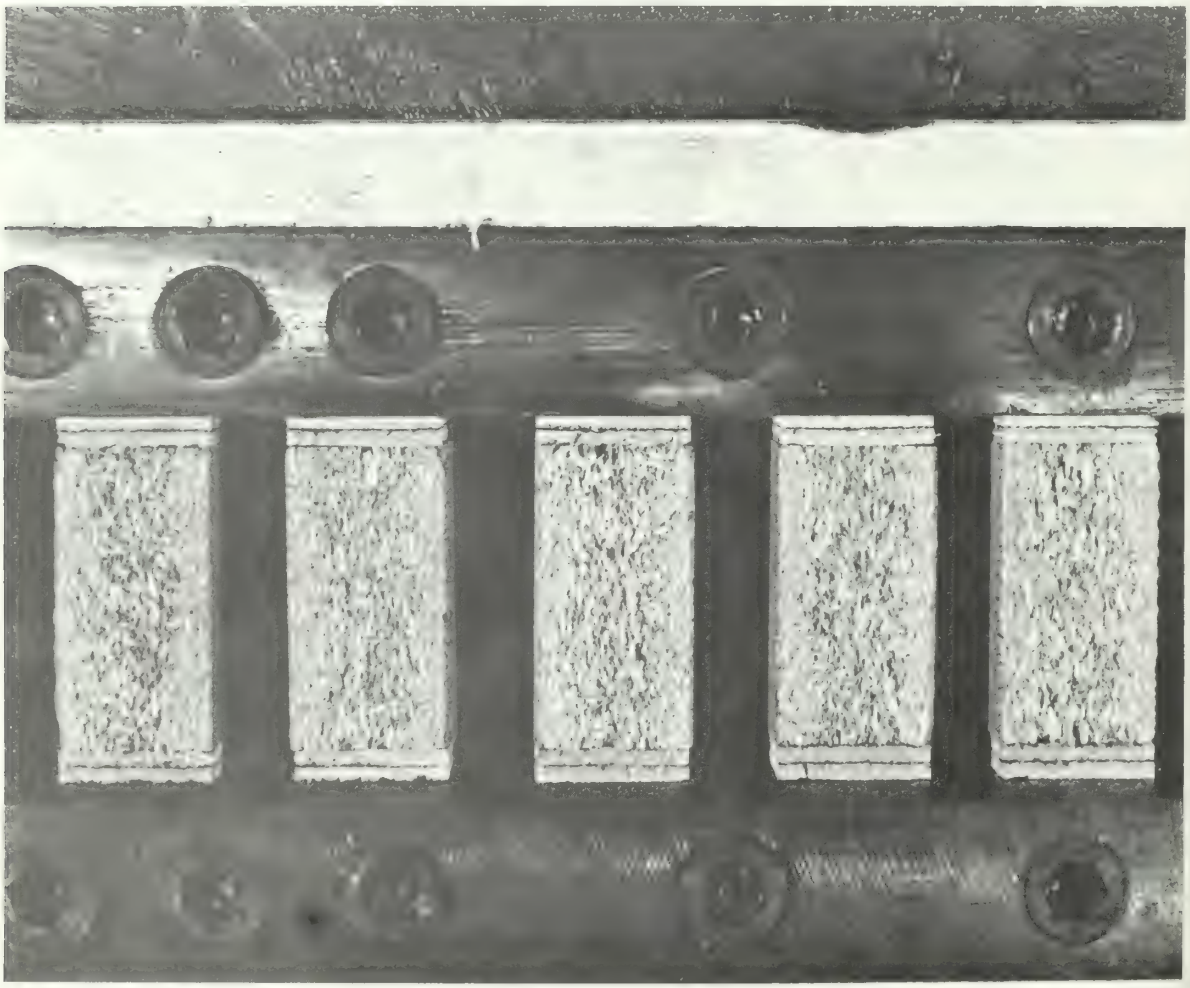

Figure 7.--Specimens in hot-press with bondlines parallel to platens.

WORKING CHARACTERISTICS

The test results in table 3 indicate that excellent bonds could be developed with these adhesives over a wide range of assembly conditions. With formula FSL-2, satisfactory bonds developed at closed assembly times from 20 minutes up to 2 hours (tests 5 and 7). A 5-minute closed assembly time was too short for double-spreads of 100 to 120 lb/Mft^2 with either adhesive (tests 1 and 4). With FSL-2, an open assembly time of 1 hour, and perhaps more, could be allowed (test 6). Although in this test the adhesive film was almost dry to the touch after 1 hour, wood failure in the bondlines was nearly 100 percent.

Table 3.--Shear strength and wood failure of particleboard-to-veneer bonds made with two modified phenolic adhesives at various assembly times and wood moisture contents

Test No. and formulation[1/]	Assembly time	Wood moisture content	Mean shear strength[2/]	Mean wood failure[2/]
	Min	Percent	Lb/in^2	Percent
1, FSL-1	5, closed	4-6	693	63
2, FSL-1	20, closed	4-6	748	85
3, FSL-1	5, closed	0[3/]	829	98
4, FSL-2	5, closed	4-6	700	73
5, FSL-2	20, closed	4-6	687	85
6, FSL-2	60, open	4-6	764	98
7, FSL-2	120, closed	4-6	773	86
8, FSL-2	5, closed	0[3/]	740	99
9, FSL-2[4/]	60, open	9-12	572	94

1/ Adhesives were double-spread at rate between 100 and 120 lb/Mft^2.
2/ Mean values based on 20 block-shear specimens.
3/ Particleboard and veneer preheated in oven at 210° F for 16 hours.
4/ Specimens cured for 5 minutes at 350° F with bondlines vertical to platens; aluminum bars were preheated to 550° to 600° F and inserted between the specimens.

Excellent bonds developed when the cores and veneer were preheated to 210° F before the adhesive was spread (tests 3 and 8). Once it was spread, the materials had to be hot-pressed immediately. Preheating the core and veneer is one method of shortening the curing time for phenolic resins. Such heat might be supplied from hot particleboard just out of the presses if the large panels could be cut quickly into core strips without rapid cooling. Perhaps infrared heaters along the production line could be used to keep the wood surfaces hot.

One method (test 9) cured the FSL-2 adhesive within 5 minutes, although it may not be a practical solution on a production line. With this method, the FSL-2 adhesive was double-spread on materials with a moisture content of 9 to 12 percent and allowed to dry for 1 hour in open assembly. The materials were then inserted in a hot-press at 350° F with bondlines vertical to the upper and lower platens, as in edge-bonding equipment. One-half-inch-thick aluminum bars preheated to 550° to 600° were inserted between the veneer laminates of adjacent studs (fig. 8). Pressure was applied to the wide faces of the studs as the adhesive cured. The heat from the upper and lower platens and aluminum bars essentially cured the adhesive within 5 minutes, and the curing was completed by overnight hot-stacking. The high temperature of the aluminum bars charred the outer veneer faces of the studs, but cooler bars might reduce this problem.

Costs of using these modified formulations would be affected by spread rate and whether the surfaces were single- or double-spread. The greatest factor

affecting costs, however, is the greater amount of resin in the modified formulations than in conventional phenolic formulations. Because water and fillers have been essentially eliminated, 25 percent more resin might be required for a modified formulation to equal the coverage of a conventional one.

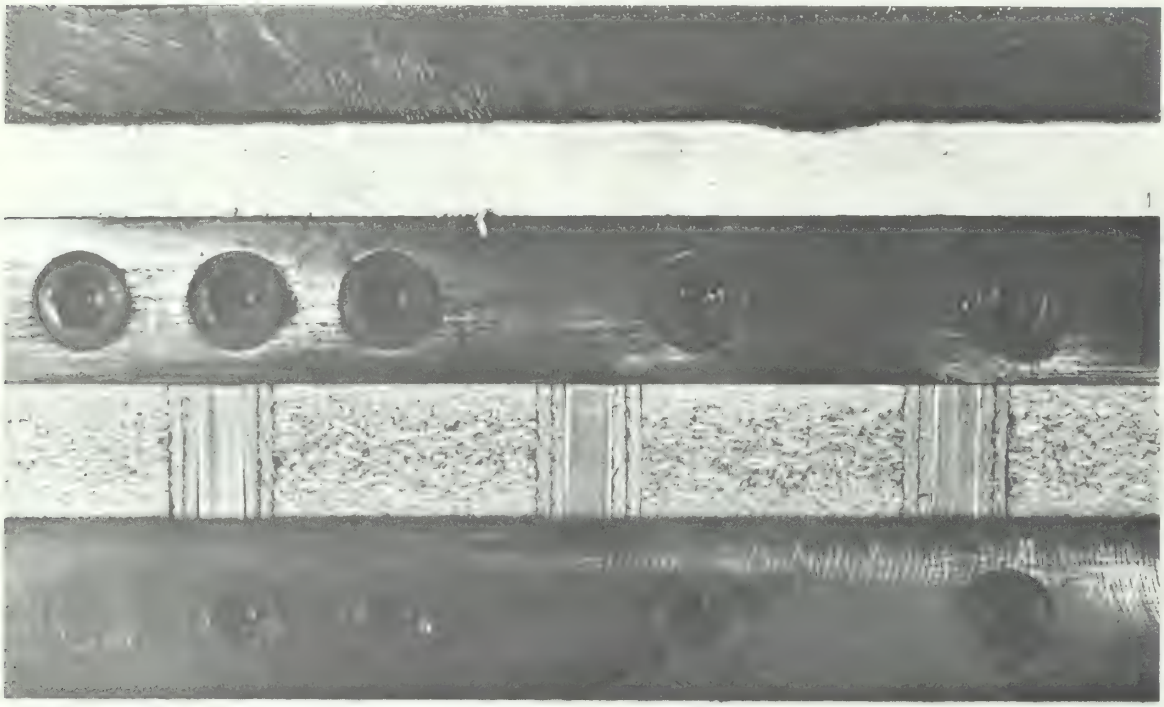

Figure 8.--Preheated aluminum bars inserted between veneer laminates to speed the curing of a modified phenolic adhesive. Bondlines are vertical to platens.

RESORCINOL-MODIFIED PHENOLIC ADHESIVES

MATERIALS AND METHODS

In another attempt to lower the cost of adhesive and speed the bonding process, we studied two experimental phenolic-type adhesives. Although these adhesives would cost more than straight phenolics, they were projected to cost about 8 to 10 cents less in bulk quantities than phenol-resorcinol adhesives. Both formulations were basically phenolic resins, but their reactivities had been increased by adding crystalline resorcinol. A para-formaldehyde hardener had also been added so that they could be spread on preheated lumber and cured immediately by hot-pressing. One of the adhesives, called HL-75® , was available only on request from the manufacturer. The other, EA-13® , would need further development before it could be made available for commercial use.

The reactivities of EA-13® , HL-75® , and a straight phenolic (the modified formulation FSL-2) were compared by measuring the gelling time for each at temperatures of 176° and 212° F. (Gelling time was defined as the time required for a column of liquid adhesive 15 mm in diameter to reach a semi-solid state after immersion in a constant-temperature water bath.) Results were as follows:

Adhesive	Gelling time at: 176° F	212° F
	(Minutes)	(Minutes)
EA-13®	2.25	0.5
HL-75®	7	2.75
FSL-2 (straight phenolic)	Did not gel	20

Although both experimental adhesives gelled in less time than the straight phenolic, EA-13® was the most reactive of the three. Tests were therefore run to determine if this adhesive could be cured within 5 minutes in simulated edge-bonding equipment. Tests were also run to determine curing times when the two experimental adhesives were spread on preheated wood surfaces.

WORKING CHARACTERISTICS

The test results in table 4 indicate that, for full strength and durability, adhesive EA-13® must be cured for about 10 minutes at 350° F when the bondlines are vertical to the platens (tests 1, 2, 5, and 8). A curing time of 7.5 minutes produced bonds that were of acceptable, but marginal, quality (tests 4 and 7). Five minutes, the target curing time for edge-bonding equipment, was too short to produce acceptable bonds (tests 3 and 6). Excellent bonds did develop within 5 minutes when aluminum bars were preheated to 550° to 600° F and inserted between the veneers of adjacent studs. As noted previously, however, the use of preheated bars may be impractical for continuous edge-bonding equipment.

Table 4.--Shear strength, wood failure, and delamination of particleboard-to-veneer bonds made with resorcinol-modified phenolic adhesive EA-13® at various adhesive spread rates, assembly times, curing times, and wood moisture contents

Test (No.)	Adhesive spread rate		Closed assembly time	Curing time[1/]	Wood moisture content	Mean shear strength	Mean wood failure	Delamination
	Particleboard	Veneer						
	----Lb/Mft²----		---Min---		Percent	Lb/in²	---Percent---	
1	80	0	10	10	6-8	647	96	0.8
2	50	30	10	10	6-8	727	91	0
3	100	0	10	5	6-8	679	74	1.9
4	100	0	10	7.5	6-8	708	79	1.2
5	100	0	10	10	6-8	702	85	0
6	60	40	10	5	6-8	676	78	0
7	60	40	10	7.5	6-8	750	83	0
8	60	40	10	10	6-8	675	94	0
9	60	40	60	5[2/]	6-8	827	92	(3/)
10	60	40	60	10	4-6	788	95	(3/)
11	60	40	60	10	9-12	740	99	(3/)

1/ Cured at 350° F with bondlines vertical to the platens.

2/ Aluminum bars were preheated to 550° to 600° F and inserted between the studs.

3/ Not tested.

With this adhesive, wood moisture contents as low as 4 to 6 percent and as high as 9 to 12 percent resulted in excellent bonds (tests 10 and 11). Closed

assembly times up to 10 minutes were allowable (tests 1-8). Excellent bonds developed with single- or double-spreads as low as 80 lb/Mft^2.

One of the most significant findings of this series of tests was that both experimental adhesives could be cured within 5 minutes in a hot-press when the bondlines were vertical to the platens and one or both wood surfaces were preheated to about 210° F (table 5). These results suggest that reactive phenolics might be cured within 5 minutes in edge-bonding equipment by utilizing the stored heat in particleboard just off the press and preheating the core edges with infrared heaters.

Table 5.--Shear strength, wood failure, and delamination of particleboard-to-veneer bonds made with two resorcinol-modified phenolic adhesives spread on preheated wood surfaces and cured at 350° F for 5 minutes with bondlines vertical to platens

Test (No.)	Adhesive spread rate		Temperature of preheated surfaces		Mean shear strength	Mean wood failure	Delamination
	Particleboard	Veneer	Particleboard	Veneer			
	----Lb/Mft^2----		°F		Lb/in^2	----Percent----	
			ADHESIVE EA-13®				
1	0	80	210 1/	72 2/	903	87	0
2	60	40	210 1/	210 1/	878	91	1.0
3	0	80	350 3/	72 2/	884	92	0
4	60	40	350 3/	72 2/	743	94	1.2
			ADHESIVE HL-75®				
5	0	80	210 1/	72 2/	795	90	0
6	60	40	210 1/	210 1/	778	96	2.2
7	0	80	350 3/	72 2/	873	88	2.9
8	60	40	350 3/	72 2/	935	99	0

1/ Wood preheated in oven at 210° F for 16 hours.

2/ Room temperature of 72° F.

3/ Edges of particleboard preheated in hot-press at 350° F for 5 minutes. Temperature 1/4 inch from surface approximately 210° F.

Tests 1, 3, 5, and 7 in table 5 suggest a practical, and perhaps economical, approach to production curing of joints in studs. In these tests, strong and durable bonds were produced by single-spreading the adhesives at a low rate (80 lb/Mft^2) on veneer at room temperature. Only the particleboard was preheated, either in an oven at 210° F or in a hot-press at 350° F. Use of such a spreading and preheating process on a production line would avoid some of the problems with precuring when adhesive is applied to hot surfaces. Continuous edge-bonding equipment would be suited for such an operation because pressure could be applied almost immediately after joining the preheated particleboard and adhesive-coated veneer.

Results of tests 2 and 6 in table 5 suggest yet another curing process. In these tests, both the particleboard and the veneer were preheated to 210° F, and the adhesives were then applied to both hot surfaces at the combined rate of 100 lb/Mft^2. There was no evidence of precuring, and the assemblies were cured with the bondlines vertical to the platens in a hot-press at 350° F for 5 minutes. Although we did not try it, preheated wood with surface temperatures near 350° F could possibly cure such adhesives without hot-presses or edge-bonding equipment.

MELAMINE-UREA AND PHENOL-RESORCINOL ADHESIVES CURED BY HIGH-FREQUENCY HEAT

MATERIALS AND METHODS

High-frequency heating has been used extensively in the furniture industry to edge-bond lumber cores. The principal advantage of this method is the speed at which heat is introduced at the point needed for adhesive curing. This speed is possible because high-frequency energy is concentrated in the bondlines rather than the wood. For exterior applications such as lumber laminations, this method has been successful in curing melamine and melamine-urea adhesives. Attempts at using high-frequency curing with the alkaline phenolic resins have not been successful, however. High concentrations of electrolytes in the phenolic adhesive cause arcing or burning of the bondlines. Straight resorcinol resins can be cured without arcing, but resin costs are too high. A phenol-resorcinol resin can also be cured without arcing if amperage is lowered and curing time is extended.

Because high-frequency curing equipment was not available at the Athens laboratory, a limited number of COM-PLY stud specimens were cured on 6-kw, radio-frequency (parallel-field) equipment by an adhesive manufacturer. We then tested the quality of the bonds at Athens.

One phenol-resorcinol and two melamine-urea adhesives were used to bond pine veneer strips to particleboard with the high-frequency equipment. One melamine-urea adhesive (A) contained 100 parts by weight of spray-dried melamine resin, 100 parts of liquid urea resin, 30 parts of walnut-shell flour, 60 parts of water, and 15 parts of catalyst. The other melamine-urea adhesive (B) contained 100 parts by weight of ready-mixed melamine-urea resin (spray-dried and filled), 60 parts of water, and 10 parts of catalyst. Ratio of melamine to urea was 1:1 in both adhesives. The third adhesive (C) contained 100 parts by weight of phenol-resorcinol and 20 parts of catalyst. Viscosities in centipoises at 70° F were 2,100 for A; 2,900 for B; and 2,400 for C.

WORKING CHARACTERISTICS

The test results in table 6 showed that all three adhesives developed shear strengths that easily exceeded the minimum requirement of 500 lb/in^2. However, none of the three met the wood failure requirement of 80 percent. The amount of delamination was not acceptable in studs bonded with the blend of liquid urea and melamine (A), but the other two performed satisfactorily in the cyclic delamination test.

Close examination of the specimens revealed that none of the three adhesives produced wood failure in summerwood bands of the southern pine veneer. The percent of wood failure was about equal to the area of springwood in the joints. As noted previously, producing wood failure in summerwood of southern pine has always been difficult. The spread rate with these adhesives was low--45 to 50 lb/Mft^2, single-spread on veneer. Increasing the spread rate, or double-spreading, with a slightly longer closed assembly time could result in bonds with greater wood failure.

These limited tests indicated that melamine-urea and phenol-resorcinol adhesives cured with high-frequency heat could not be recommended for laminating COM-PLY studs. However, it is possible that adhesives B and C could be used with some modifications of bonding conditions. The wood failure requirement seems less important when the adhesive has adequate dry strength and shows good resistance to delamination.

Table 6.--Shear strength, wood failure, and delamination of particleboard-to-veneer bonds made with one phenol-resorcinol and two melamine-urea adhesives cured with high-frequency heat[1/]

Adhesive	Rate of single-spread	Closed assembly time	Edge pressure	Radio frequency current (start/end)	Curing time	Mean shear strength	Mean wood failure	Delamination
	Lb/Mft^2	Min	Lb/in^2	Amp	Min	Lb/in^2	Percent	
Melamine-urea (A)	45-50	5-10	150	1.25/0.75	1.5	665	58	15.1
Melamine-urea (B)	45-50	5-10	150	1.5/0.80	1.5	752	63	.9
Phenol-resorcinol (C)	45-50	0	150	0.8/0.70	2	691	56	2.8

1/ Data on bonding conditions reported by the adhesive manufacturer. Data on bond quality determined by the Wood Products Research Unit at Athens, Ga.

SUMMARY

These limited studies indicate that COM-PLY studs can be manufactured with any one of several adhesives on standard production equipment. These adhesives can produce strong, durable bonds between strips of veneer and particleboard cores. It remains to be seen which combination of adhesive and curing equipment will prove most economical in terms of costs per stud for adhesive, spreading and curing equipment, and energy and manpower requirements.

The various tests can be summarized as follows:

1. Laboratory tests demonstrated that acceptable bonds in COM-PLY studs were produced by a commercial phenol-resorcinol-formaldehyde adhesive cured in a hot-press simulating a production-type, edge-bonding machine. Although the adhesive is costly, the bonding operation was simple and rapid. Initial curing occurred within 5 minutes or less at 350° F, and curing was completed by hot-stacking overnight. The adhesive was single- or double-spread at rates of 80 to 100 lb/Mft^2, with an allowable closed assembly time of up to 10 minutes. So successful were these tests that a phenol-resorcinol adhesive was selected for pilot manufacturing of COM-PLY studs in a factory.

2. A commercial phenol-resorcinol-formaldehyde adhesive diluted with water and then filled to its original consistency with walnut-shell flour developed bonds of acceptable quality in COM-PLY studs. Concentration of resin solids was reduced from the normal 45 percent to approximately 30 percent, thereby extending the adhesive coverage by about 33 percent. The diluted adhesive was single- or double-spread at rates of 90 to 100 lb/Mft^2--a slightly heavier spread rate than for undiluted adhesive--with an allowable closed assembly time of up to 10 minutes. The diluted adhesive was cured in the same time as the undiluted formulations. Overall savings in cost of adhesive with the diluted formulation would be nearly 20 percent.

3. A commercial phenolic adhesive for southern pine plywood overpenetrated the particleboard cores of COM-PLY studs and failed to form acceptable bonds between the veneer and particleboard. This problem of overpenetration was solved by reducing the amount of water in the commercial mixture and allowing long assembly

time. Content of resin solids approximated 36 percent in the modified adhesive--an 8 percent increase over that of the commercial formulation. This increase meant that approximately 25 percent more resin was needed to equal the coverage of the commercial mixture. Consequently, use of the modified adhesive would involve a proportionate 25 percent increase in cost.

The modified phenolic cured satisfactorily under a wide range of assembly conditions. When double-spread, it needed a minimum closed assembly time of 20 minutes, but a closed assembly time of 2 hours or an open assembly time of 1 hour was acceptable. Curing time for this adhesive was approximately 15 minutes at 350° F when bondlines were vertical to the platens, as in an edge-bonding machine. Excellent bonds developed when the adhesive was spread on preheated wood at 210° F and then hot-pressed with veneers directly touching the platens. The adhesive was cured within 5 minutes by inserting aluminum bars preheated at 550° to 600° F between adjacent studs.

4. Two resorcinol-modified phenolic adhesives, more reactive than straight phenolics and lower in cost than phenol-resorcinols, were applied to preheated wood surfaces and cured within 5 minutes in equipment simulating an edge-bonder. Bonds were cured even faster when heat was applied directly to the veneered faces. The adhesives were single- or double-spread at rates as low as 80 lb/Mft^2. Successful bonds were produced over a wide range of wood moisture contents and with extended assembly times.

5. Tests of melamine-urea and phenol-resorcinol bonds cured by high-frequency heat were limited and inconclusive. Further efforts should be made to find phenolic-based adhesives that can be cured by this method.

RECOMMENDATIONS

Energy is wasted when COM-PLY studs bonded with relatively slow phenolic adhesives are cured in an edge-bonding machine. Because the bondlines are vertical to the platens, they can only be cured by heating the entire stud to a high temperature. Heat would be better utilized and the adhesive cured faster if the veneer faces were heated directly with the bondlines parallel to the platens. Thus, methods should be devised for curing phenolic-bonded studs in flat-platen hot-presses similar to those used in manufacturing plywood. The use of preheated wood surfaces as a means of curing phenolic resins more rapidly should also be investigated further.

Another economy measure that should be explored is the production of a particleboard with smooth edges for bonding to veneer. Use of such particleboard could cut spread rates, and hence the cost of adhesives, by 20 to 30 percent.

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Several adhesives and bonding techniques have been initially evaluated for use in factory lamination of veneer strips to particleboard cores in COM-PLY studs. Phenolic-base resin adhesives, whether modified with resorcinol or not, produced strong, durable bonds and showed promise for reducing costs. Flat platens, preheated wood, and high-frequency curing merit more investigation as ways to speed curing of such adhesives in COM-PLY studs.

KEYWORDS: Composite lumber, phenolic adhesive, phenol-resorcinol adhesive, resorcinol-modified phenolic adhesive, melamine-urea adhesive, performance requirements, bonding techniques.

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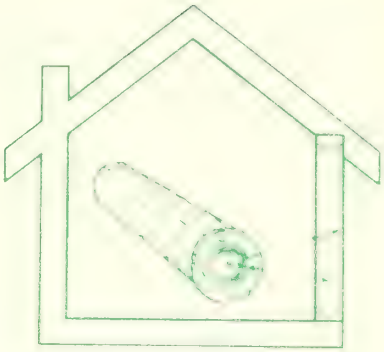

COM-PLY 7 REPORT

DURABILITY AND DIMENSIONAL STABILITY OF COM-PLY STUDS

COOPERATIVE RESEARCH

DURABILITY AND DIMENSIONAL STABILITY OF COM-PLY STUDS

by

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Cooperative Research by

U.S. Department of Agriculture, Forest Service

Southeastern Forest Experiment Station

and

U.S. Department of Housing and Urban Development

Division of Energy, Building Technology

and Standards

PREFACE

This report is one of a series on the possibilities of producing house framing and structural panels with particleboard cores and veneer facings. These COM-PLY or composite materials were designed to be used interchangeably with conventional lumber and plywood in homes. Research on structural framing is presently limited to COM-PLY studs but will be extended to include larger members such as floor joists.

In 1973, the home-building industry faced a shortage of lumber and plywood and consequent rising prices. Both industry and government recognized that this situation was not a temporary problem, and that long-range plans for better using the Nation's available forest resources would be necessary.

The USDA Forest Service and the U.S. Department of Housing and Urban Development accelerated cooperative research on ways to utilize the whole tree. They concentrated on composite wood products made with particleboard and veneer as a way of using not only more of the tree stem, but also using less desirable trees and a greater variety of tree species than would conventional wood products. The particleboard which comprises a large portion of the COM-PLY stud is made from ground-up wood that comes from forest residues, mill residues, or low-quality timber. Thus, such composites could greatly increase the amount of lumber and plywood available for residential construction, our major use of wood, without eroding the Nation's timber supply.

Research on composite wall framing was performed by the Wood Products Research Unit, Southeastern Forest Experiment Station, Athens, Georgia. The American Plywood Association cooperated in these studies by designing and testing composite panel products that are interchangeable with plywood. Both types of products have been incorporated in demonstration houses.

Included in this series will be reports on structural properties, durability, dimensional stability, strength, and stiffness of composite studs. Other reports will describe the overall project, compare the strength of composite and solid wood studs, suggest performance standards for composite studs, and provide construction details on houses incorporating such studs. Still others will explore the economic feasibility of manufacturing composite studs and panels and estimate the amount and quality of veneer available from southern pines. These reports, called the COM-PLY series, will be available from the Southeastern Forest Experiment Station and the U.S. Department of Housing and Urban Development.

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DURABILITY AND DIMENSIONAL STABILITY OF COM-PLY STUDS

Abstract.--This report describes the strength, deflection, dimensional stability, and warpage of COM-PLY studs before and after accelerated aging in the laboratory and outdoor weathering. These properties changed only slightly after 1 year of weathering, and COM-PLY studs met the requirements for durability and dimensional stability as specified by "Performance Standards for Composite Studs Used in Exterior Walls."

KEYWORDS: Weathering, warpage, composite lumber, Performance Standards.

Through cooperative research, the USDA Forest Service and the U.S. Department of Housing and Urban Development have developed a new composite lumber product called the COM-PLY stud. Designed to utilize trees and wood residues more efficiently, this product, a sandwich construction, consists of approximately 80 percent particleboard and 20 percent veneer of solid wood. The phenolic-bonded particleboard serves as a core, and a double layer of veneer is laminated to each of its narrow edges (fig. 1).

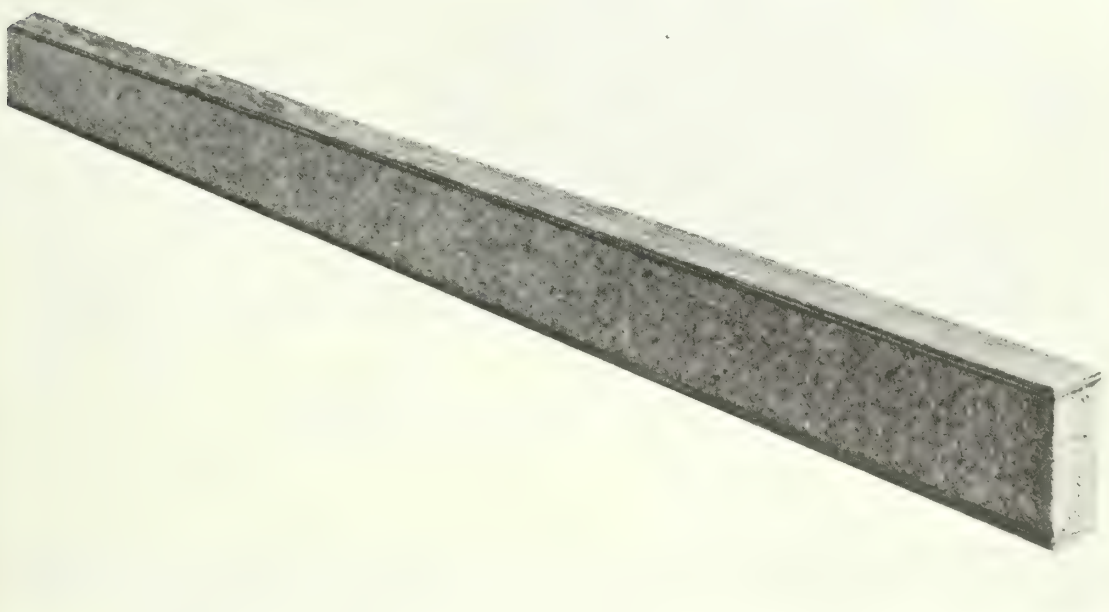

Figure 1.--COM-PLY stud consisting of particleboard core with veneer bonded to the narrow edges.

Code officials, builders, and other potential users will only accept COM-PLY studs for residential wall construction if the studs have the necessary durability and dimensional stability. These properties should be sufficient for the studs to withstand the changes in temperature and moisture content which would affect them

during storage, on-site construction, and long-term use in the finished wall (fig. 2). Such conditions should cause only minimal loss in strength and little or no dimensional change. Performance Standards for determining whether COM-PLY studs have acceptable durability and dimensional stability for light-frame construction have been established by the Wood Products Research Unit of the Southeastern Station in cooperation with the Department of Housing and Urban Development.[1]

This paper reports on laboratory tests conducted to evaluate COM-PLY studs for durability and dimensional stability in accordance with the Performance Standards, additional tests of these properties after outdoor exposure, and a comparison of the dimensional stability of COM-PLY studs and of those of solid spruce.

SELECTING MATERIALS FOR TEST STUDS

For the tests, researchers used 150 COM-PLY studs fabricated from phenolic-bonded particleboard (40 pounds per cubic foot) pressed to a thickness of 1-1/2 inches. The particleboard was cut into cores 1-1/2 inches thick, 2-7/8 inches wide, and 8 feet long. Veneer for the COM-PLY studs was B and better grade southern pine 1/6 inch thick, 1-1/2 inches wide, and 8 feet long. Pairs of veneer strips were parallel-laminated with phenol-resorcinol at a spread rate of 45 pounds per 1,000 square feet of glueline. Upon curing, the laminated veneer strips were glued to the narrow edges of the particleboard cores with the same adhesive and at a spread rate of 90 to 100 pounds per 1,000 square feet of glueline.

Two groups of COM-PLY studs were used in the tests. Studs evaluated for durability and dimensional stability in the laboratory were manufactured in a pilot plant run at Champion-International's U.S. Plywood particleboard plant at South Boston, Virginia. Studs evaluated after exposure on an exterior fence were fabricated in the laboratory. The two groups of studs contained identical types of veneers, particleboard cores, and laminating adhesives, and both groups had high-quality adhesive bonds.

For the comparison of COM-PLY with solid studs, researchers bought 20 white spruce [*Picea glauca* (Moench) Voss] studs, all of stud grade, from several local lumber yards. No attempt was made to pre-select the studs for straightness, grain orientation, or moisture content.

Before testing, researchers conditioned all studs to a moisture content of 10 $\pm$ 2 percent.

DURABILITY TEST: LABORATORY EVALUATION

METHODS

Researchers randomly selected 40 COM-PLY studs for accelerated aging and laboratory testing according to the Performance Standard for durability. They designated 20 of these studs as controls and tested them for ultimate load and deflection at 225 pounds of total load (fig. 3). These studs were subjected to

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[1]Blomquist, Richard F., John E. Duff, Gerald A. Koenigshof, Robert H. McAlister, and Dick C. Wittenberg. 1976. Performance standards for composite studs used in exterior walls. U.S. Dep. Agric., For. Serv., Res. Pap. SE-155, COM-PLY Rep. 2, 24 p. U.S. Dep. Agric., For. Serv., Southeast. For. Exp. Stn., Asheville, N.C.

edgewise bending loads at the quarter points and an axial compressive load of 1,190 pounds on the end until failure occurred. Data on load and deflection were recorded and average values computed for the controls.

Figure 2.--COM-PLY studs stored at a construction site. Note studs already in place as wall framing.

Researchers used these averages to calculate the adjusted bending strength and deflection for the controls according to the formulas in the Performance Standard. These values were later compared with the corresponding adjusted values for the studs that underwent accelerated aging.

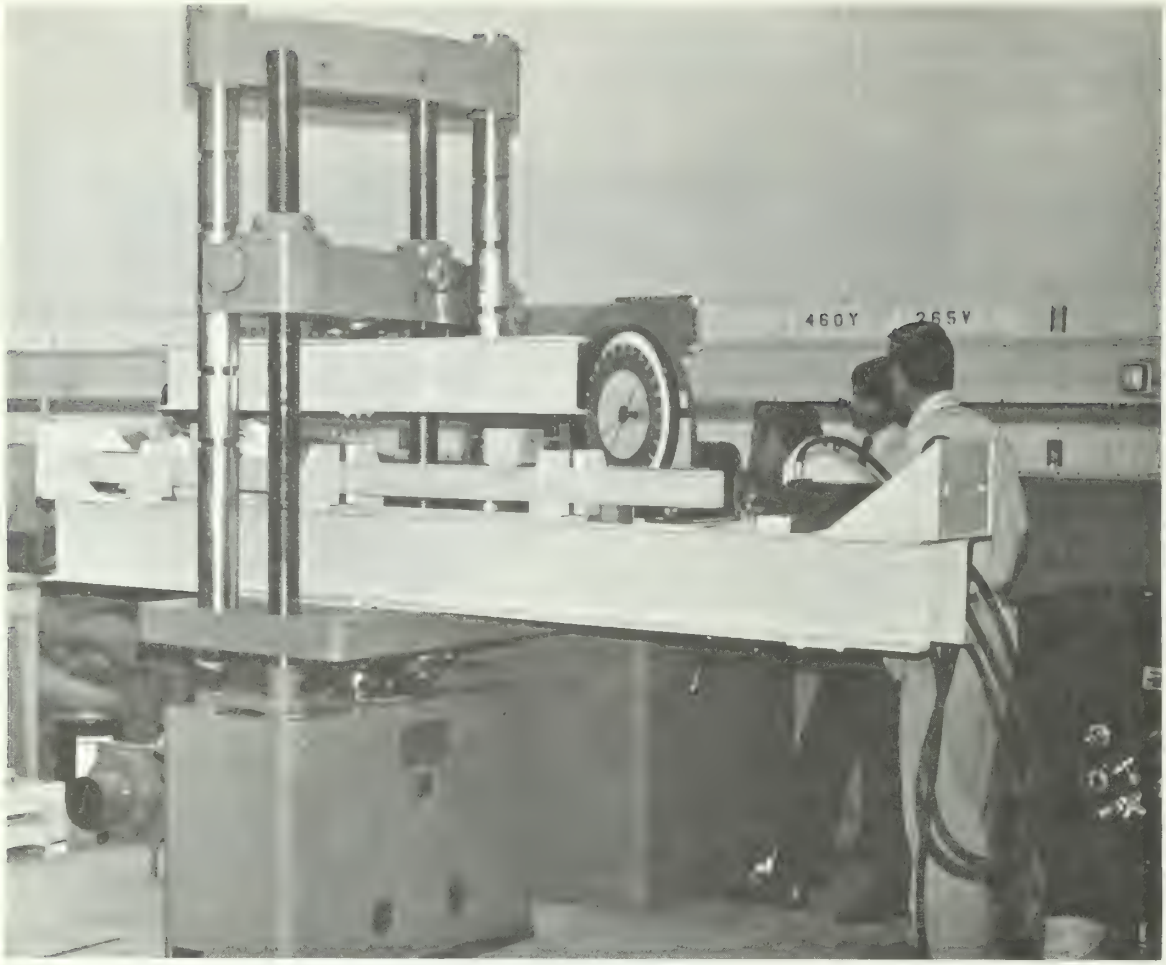

Figure 3.--A COM-PLY stud in a universal testing machine.

The remaining 20 studs were subjected to six cycles of accelerated aging, each cycle consisting of the five exposures described below:

1. Immersed in water at 120° ± 3° F (49° ± 2° C) for 1 hour.
2. Sprayed with steam and water vapor at 200° ± 5° F (93° ± 3° C) for 3 hours.
3. Heated at 210° ± 3° F (99° ± 2° C) in dry air for 3 hours.
4. Repetition of step 2.
5. Heated in dry air at 210° ± 3° F (99° ± 2° C) for 18 hours.

For soaking and steaming, researchers placed the studs in a steel tank (fig. 4). For steps 3 and 5, the studs were dried in a forced-air dry kiln.

Figure 4.--COM-PLY studs in steam tank just before testing.

After undergoing accelerated aging, the COM-PLY studs were reconditioned to a moisture content of 10 $\pm$ 2 percent. Researchers then tested the exposed studs for bending strength and deflection and calculated the adjusted values for these properties. These adjusted values were compared with the values set by the Performance Standard.

RESULTS

After the COM-PLY studs underwent accelerated aging in the laboratory (fig. 5), the adjusted bending load decreased from 73.2 to 61.4 pounds per linear foot of stud. However, this value easily exceeded the minimum strength requirement of 20 pounds per linear foot in the Performance Standard.

Adjusted deflection after the studs underwent accelerated aging decreased from 0.288 to 0.257 inch, remaining less than the 0.824-inch maximum allowed by the Performance Standard. Adjusted deflection decreased because the studs had a lower standard deviation in deflection values after the aging than before it, although this difference was not statistically significant at the 5 percent level.

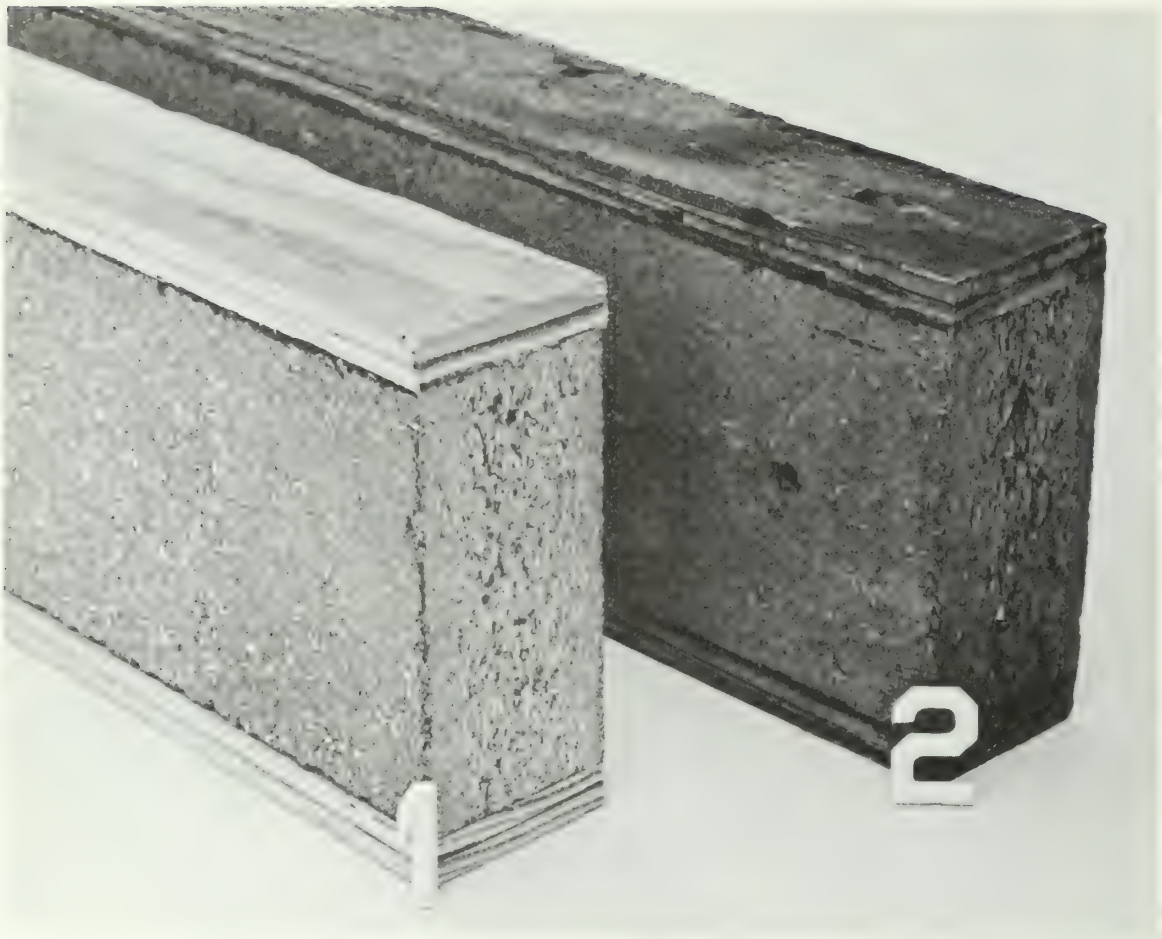

Figure 5.--Unexposed COM-PLY stud (1) and stud exposed to accelerated aging (2).

DURABILITY TEST: FENCE EXPOSURE

Some researchers believe that accelerated aging in the laboratory as specified in the Performance Standard for durability is unrepresentative of the weathering COM-PLY studs would undergo during on-site construction. Therefore, an exposure test that better approximates actual service conditions was adopted to supplement the data from the accelerated aging test, even though results of the two tests should not be compared.

In choosing an additional exposure test, researchers tried to simulate the worst conditions COM-PLY studs would likely encounter from the time they are manufactured until they are installed in a finished wall. This exposure would probably occur during on-site construction if the COM-PLY studs are installed in wall frames without roof protection for extended periods. Such exposure was simulated by installing COM-PLY studs in an outdoor test fence (fig. 6) and assessing their strength retention after 12 months.

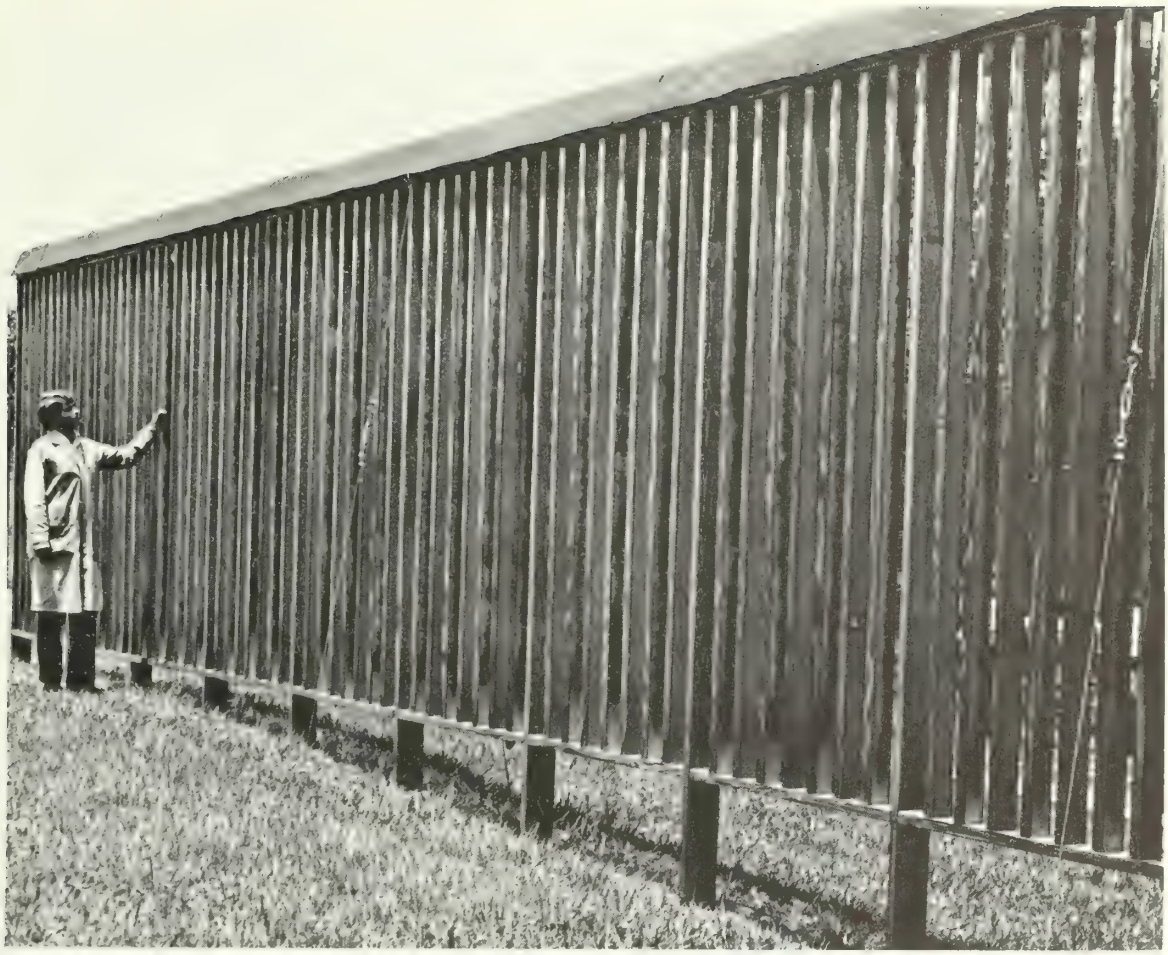

Figure 6.--COM-PLY studs on a test fence at Athens, Ga.

METHODS

Researchers conditioned 90 COM-PLY studs to a moisture content of 10 ± 2 percent. They chose 18 studs at random as controls and tested them for bending strength and deflection according to the Performance Standard for durability. This test omitted the end loading used in the laboratory evaluation. These data were later compared with test values after the remaining studs were exposed.

The remaining 72 COM-PLY studs were toe-nailed upright on the test fence. This fence stands on an open, gently sloping hillside. The studs were positioned at 8-inch intervals along the test fence with one veneered face of each stud facing south.

After 12 months of weathering, researchers removed 18 studs, conditioned them to a moisture content of 10 ± 2 percent, and tested them for bending strength and deflection according to the Performance Standard for durability.

RESULTS

Adjusted bending load of the test studs was 65.2 pounds per linear foot before exposure on the test fence and 69.6 pounds after 12 months' exposure (fig. 7). Although bending strength apparently increased with exposure time, the increase

was not statistically significant at the 5 percent level. Adjusted deflection of the studs at 225 pounds of load was 0.370 inch before exposure and 0.399 inch after 12 months' exposure. Thus, a year's exposure slightly reduced the average stiffness of the studs. As with the laboratory test, however, strength and stiffness of the studs after exposure on the test fence met the requirements of the Performance Standard.

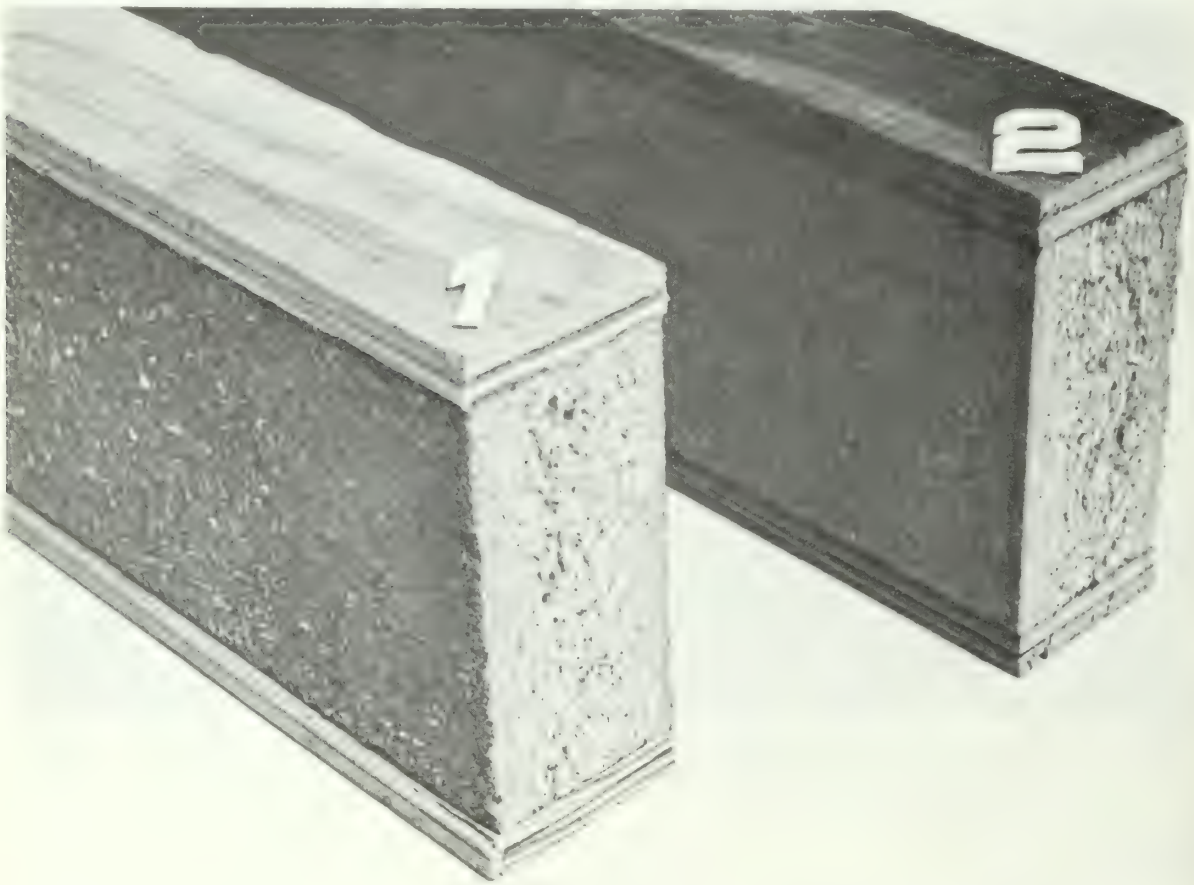

Figure 7.--COM-PLY studs before exposure on the test fence (1) and after 12 months' exposure (2).

DIMENSIONAL STABILITY TEST: LABORATORY EVALUATION

METHODS

Researchers assessed dimensional stability in the laboratory by measuring 20 COM-PLY studs and 20 spruce studs for dimensional change and warpage after water soaking. Before the soaking, the width (3-1/2-inch dimension) and thickness (1-1/2-inch dimension) of the various studs were each measured at three points along the stud's length (fig. 8) with an adjustable caliper (0 to 4 inches) incremented to 0.001 inch. Length was determined by measuring a 90-inch distance along each stud with a 45-inch bar gage. This bar gage consisted of a fixed pin at one end and a movable dial gage with a reference pin at the other end. The dial gage

measured differences of 0.001 inch. For the gage, researchers drilled two 1/8-inch holes 90 inches apart along the centerline of the 3-1/2-inch dimension; each hole was located 3 inches from one end of the stud. A third hole was drilled at the midpoint of the gage length. Researchers determined the total gage length by measuring the distance between the midpoint and the holes at each end and then adding the results. In this way, subsequent changes in length after water soaking could be determined for each stud.

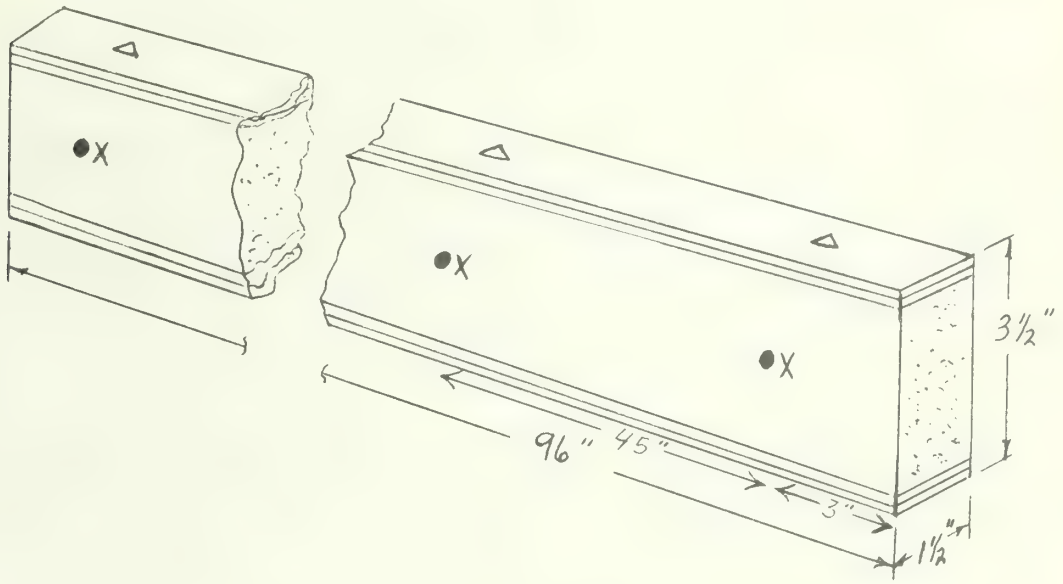

Figure 8.--The six measurement points (X's and Δ's) along the 96-inch dimension of the stud. Note the three holes drilled in the 3-1/2-inch face for the bar gage.

Note that this procedure for measuring the length of the studs differs from the one specified in the Performance Standard for dimensional stability. Although the two methods yield equivalent results, the method described in the Standard is more convenient.

After the initial measurements, all studs were placed in a long steel tank, separated by 1/2-inch wood strips, and submerged in fresh tapwater at room temperature for 24 hours. After soaking, the studs were drained and remeasured while wet for dimensional change and warpage (bowing, crooking, and twisting). Test values were compared with limits set by the Performance Standard.

RESULTS

Although the Performance Standard allows an 8 percent change in the 3-1/2-inch and 1-1/2-inch dimensions after 24 hours of water soaking, the average change in the 20 COM-PLY studs was only 2.8 percent in the 1-1/2-inch dimension and 1.0 percent in the 3-1/2-inch dimension (table 1). The 90-inch linear dimension changed 0.03 percent after the soaking, well within the limit of 0.1 percent specified in the Performance Standard.

Table 1.--Dimensional change in COM-PLY and spruce studs immediately after 24 hours of water soaking and limits set by the Performance Standard

Dimension	Dimensional change		Performance Standard limits
	COM-PLY	Spruce	
	- - - - - - - - Percent - - - - - - - -		
3.5-inch	1.0	0.8	8.0
1.5-inch	2.8	1.0	8.0
90.0-inch	.03	.02	.1

Comparison of the average dimensional change in the 20 COM-PLY and 20 spruce studs indicated that both changed about equally in the 3-1/2-inch face (table 1). Researchers consider the 3-1/2-inch face the most critical dimension of the stud when builders strive for a smooth finished wall and a minimum of nail popping. In the 1-1/2-inch dimension, the change in the spruce studs (1.0 percent) was less than in the COM-PLY studs (2.8 percent). The change in the COM-PLY studs, however, amounted to only about 0.042 inch. In terms of wall framing, this amount is not significant, especially when confined to a direction parallel to the length of the wall.

Dimensional change in length was about equal for the two types of studs (0.03 percent for COM-PLY and 0.02 percent for spruce). Linear change in the COM-PLY studs was slight because the laminated veneers restrained dimensional change in the particleboard core. Without this restraint, the core probably would have changed about 1 percent.

Both builders and consumers need to know how much COM-PLY studs will warp between the time they are manufactured and the time they are installed in a wall. If a stud is straight when made from dry materials, it should not warp excessively when it becomes wet. The average bow, crook, and twist of the 20 COM-PLY studs before and after they were water-soaked for 24 hours confirm this conclusion (table 2). In no dimension did this warpage exceed the limits set by the Performance Standard. Cupping in the COM-PLY studs was also negligible.

Table 2.--Warpage of COM-PLY and spruce studs before and after 24 hours of water soaking and warpage limits set by the Performance Standard

Warpage type	Warpage				Performance Standard limits
	COM-PLY		Spruce		
	Before soaking	After soaking	Before soaking	After soaking	
	- - - - - - - - - - Inch - - - - - - - - - -				
Bow	0.063	0.093	0.205	0.179	0.750
Crook	.039	.142	.153	.128	.250
Twist	.000	.011	.258	.248	.375

After the soaking, warpage (bow, crook, and twist) of the COM-PLY studs increased slightly whereas that of the spruce studs decreased (table 2). This difference arose because the spruce studs were more distorted than the COM-PLY studs before the soaking. Solid studs such as spruce are sawn while green and often warp from internal stresses as they dry. Rewetting solid studs usually does not significantly increase the amount of warpage and, in this case, actually caused it to decrease. In neither case, however, did the amount of warpage after soaking exceed the limits set by the Performance Standard.

DIMENSIONAL STABILITY TEST: FENCE EXPOSURE

METHODS

As with the laboratory test for durability, some researchers have questioned whether soaking COM-PLY studs in water for 24 hours is adequate to assess their dimensional stability. Accordingly, the same COM-PLY studs tested for durability after exposure for 12 months on the outdoor fence were also measured for dimensional change and warpage. Measurements from the outdoor and laboratory tests were then compared.

Dimensional change after 12 months' exposure on the fence was less than the values recorded after 24 hours of water soaking (table 3). These results indicate that soaking for 24 hours is a suitable test for evaluating the dimensional stability of COM-PLY studs.

Table 3.--Dimensional change in COM-PLY studs after 24 hours of water soaking or exposure on a test fence for 12 months

Dimension	Dimensional change	
	After soaking	After 12 months' fence exposure
	- - - - Percent - - - -	
3.5-inch	1.0	0.3
1.5-inch	2.8	2.1
90.0-inch	.03	.00

Regardless of whether the studs were soaked in water or exposed on the fence for 12 months, the resulting bow, crook, and twist did not exceed 0.228 inch (table 4). Because these amounts of warpage are so small, it is difficult to determine which exposure test is more effective for evaluating this property The tests do show, however, that COM-PLY studs do not warp appreciably from water soaking or exposure to weathering.

Table 4.--Warpage of COM-PLY studs before and after 24 hours of water soaking or exposure on a test fence for 12 months

Warpage type	Water soaking		Fence exposure for 12 months	
	Before	After	Before	After
	- - - - - - - - - - Inch - - - - - - - - - -			
Bow	0.063	0.093	0.120	0.228
Crook	.039	.142	.059	.096
Twist	.000	.011	.013	.050

CONCLUSIONS

A stud that is about 20 percent veneer of solid wood and 80 percent particleboard will meet the Performance Standards for durability and dimensional stability in light-frame construction. In the tests reported here, such COM-PLY studs outperformed spruce studs in the laboratory test for dimensional stability and also met the requirements for structural strength and stiffness after 1 year of outdoor weathering. Thus, builders can store or install COM-PLY studs without protection from weathering at the construction site and expect no serious loss in strength or change in dimension.

Duff, John E.
1977. Durability and dimensional stability of COM-PLY studs. USDA For. Serv. Res. Pap. SE-172, COM-PLY Rep. 7. 12 p. Southeast. For. Exp. Stn., Asheville, N. C., and U. S. Dep. Housing and Urban Develop., Washington, D. C.

This report describes the strength, deflection, dimensional stability, and warpage of COM-PLY studs before and after accelerated aging in the laboratory and outdoor weathering. These properties changed only slightly after 1 year of weathering, and COM-PLY studs met the requirements for durability and dimensional stability as specified by "Performance Standards for Composite Studs Used in Exterior Walls."

KEYWORDS: Weathering, warpage, composite lumber, Performance Standards.

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DA Forest Service Research Paper SE-173 December 1977

Growth and Development of Thinned Versus Unthinned Yellow-Poplar Sprout Clumps

by

Donald E. Beck

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Southeastern Forest Experiment Station
Asheville, North Carolina

Growth and Development of Thinned Versus Unthinned Yellow-Poplar Sprout Clumps

by

Donald E. Beck, Principal Silviculturist
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Abstract.--Yellow-poplar stump sprouts are capable of very rapid growth and often dominate stands on good sites following harvest cutting. Thinning to one stem per stump at 6 years of age did not affect either height or diameter growth over the succeeding 18 years. The untreated clumps thinned themselves to an average of two stems per clump during the same time period. Thinning to one stem had no apparent effect on butt rot potential from the parent stump, but did reduce the potential for rot from dying ancillary stems.

Keywords: Height growth, diameter growth, butt rot, mortality, fungi, multiple stems, stumps.

When yellow-poplar (Liriodendron tulipifera L.) is harvested in second-growth stands, its stumps sprout prolifically. Wendel found that 97 percent of the yellow-poplar stumps produced sprouts on two harvested areas in West Virginia.[1] Trees ranging from 6 to 22 inches in diameter produced an average of 42 sprouts per stump 1 year after harvest. True reported an average of 21 sprouts on 1-year-old yellow-poplar stumps ranging from 6 to 26 inches in diameter.[2] As the size of the stump increased, the percentage of stumps sprouting and the number of sprouts per stump decreased. But even stumps as large as 26 inches produced eight or more sprouts. Similar observations have been made throughout the Southern Appalachians.

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[1] Wendel, G. W. 1975. Stump sprout growth and quality of several Appalachian hardwood species after clearcutting. USDA For. Serv. Res. Pap. NE-329, 9 p. Northeast. For. Exp. Stn., Upper Darby, Pa.

[2] True, R. P. 1953. Studies on sprout reproduction of yellow-poplar as related to decay. W. Va. Agric. Exp. Stn. Curr. Rep., 3 p.

Because yellow-poplar stump sprouts grow faster than yellow-poplar seedlings and sprouts of other species, they often comprise a significant portion of new stands that develop after harvest of mature second-growth stands. To effectively manage stump-sprout stands the forester needs to understand the development of sprout clumps, their potential for producing desirable crop trees, and the cultural practices that enhance development of sprouts into desirable crop trees.

The major objective of the study was to determine if thinning of sprout clumps affects the growth rate of remaining trees. The study also provided the opportunity to examine development of stump sprouts and their suitability as crop trees.

METHODS

The study was conducted on the Bent Creek Experimental Forest in western North Carolina at an elevation of about 2,400 feet. Two groups of 60 sprout clumps each were selected in an area that had been commercially harvested 6 years previously. One group of sprout clumps was on an east-facing slope with a site index for yellow-poplar of about 110 feet at 50 years. The other group of sprout clumps was located in a streambottom where, probably due to poor drainage, site index for yellow-poplar was only about 80 feet at 50 years.

Within each sprout clump, the single best tree was designated as a crop tree on the basis of size, form, and location on the stump. Only sprouts originating at or below ground line were chosen as crop trees. Measurements made for each clump included:

1. Diameter of the originating stump.

2. Total number of sprouts on each stump.

3. Number of sprouts likely to compete strongly with the selected tree; i.e., sprouts nearly equal in size to selected crop tree.

4. Height and diameter of the selected tree.

Within each block, half the clumps were designated at random to be treated. Treatment consisted of cutting all sprouts in a clump except the designated crop tree. The other half of the clumps were left unthinned.

Height and diameter measurements of the designated crop trees were made 6, 12, and 18 years after treatment. When the study stumps were created in 1952 by a commercial harvest, trees up to 12 inches d.b.h. were left standing. The residual trees overtopped and suppressed some of the treated sprout clumps by 1975. Consequently, only sprout clumps that were not suppressed were analyzed for thinning effects. A total of 71 sprout clumps, well distributed by treatment and block (table 1), was included.

Table 1.--Pretreatment conditions for 71 stumps used in treatment analysis

	Clumps	Initial sprouts		Stump diameter		Crop tree height		Crop tree diameter	
		Average	Range	Average	Range	Average	Range	Average	Range
	- - - - Number - - - -			- - Inches - -		- - Feet - -		- - Inches - -	
Poor site									
Thinned	18	7.4	1-16	18.9	12-26	23	16-31	2.2	1.5-3.2
Unthinned	20	7.0	2-14	20.7	4-28	25	15-35	2.6	1.4-4.8
Good site									
Thinned	18	5.3	2-9	15.3	6-25	28	19-37	3.0	1.9-4.4
Unthinned	15	5.7	2-11	13.8	8-20	29	21-40	3.2	2.3-4.4

RESULTS

STATUS OF SPROUT CLUMPS AT AGE 6

At age 6 there was an average of 6.4 sprouts per stump but only half of the sprouts (3.1) were considered strong enough to survive (table 1). There was a maximum of 20 sprouts on the 6-year-old stumps, and only 15 stumps (21 percent) had more than 10 sprouts. Assuming that the stumps produced more sprouts shortly after cutting--as indicated by Wendel's and True's findings (see footnotes 1 and 2)--there had already been considerable mortality during the first 6 years. In Wendel's study, the average of 42 sprouts per stump at age 1 had dwindled to five sprouts 10 years after harvest.

There was no relationship between stump size and number of sprouts at age 6 or between stump size and number of strong competitors. If smaller stumps tend to produce more sprouts as reported by True (see footnote 2), differential mortality had obliterated this tendency in 6 years.

Stems that attained nearly 40 feet in height and 5 inches in diameter by age 6 demonstrated the exceptional growth of yellow-poplar stump sprouts. There was no relationship between size of crop tree sprouts and size of stump.

EFFECT OF THINNING

Stump size was tested as a possible covariant in the analysis of treatment effects. However, both height and diameter growth were independent of parent stump size. Sprouts from stumps as small as 4 inches grew at the same rates as sprouts from stumps as large as 32 inches.

Thinning at age 6 to a single stem per stump did not affect height growth during the subsequent 18-year period. On the good site the treated stems grew 52 feet in height as opposed to 51 feet for untreated stems. Although on the poorer site the untreated stems actually outgrew the treated ones (33 feet vs. 27 feet), this difference was not statistically significant. Analysis of height growth by 6-year periods showed that there was neither a short-lived response to thinning nor a delayed one masked by lumping growth periods (table 2).

As was the case with height growth, thinning to a single stem per stump did not significantly affect diameter growth of crop trees (table 3). On the good site slightly, but not significantly, greater growth occurred on the treated stems than on untreated stems. On the poor site the untreated stems had greater diameter growth in the second- and third-growth periods than the treated stems. This difference is not believed to be correlated to treatment, but to a rising water table which affected treated stems more than untreated stems due to their positions in the block. In contrast, the height and diameter results on the good site are believed to be typical for good yellow-poplar sites.

Following thinning, most treated stumps produced from 1 to 25 new sprouts. The average for treated clumps was five new sprouts per stump. However, these new sprouts grew very little and died quickly. Only two or three of the new sprouts were still alive 18 years after treatment. Thus, resprouting posed no threat to the selected crop tree in thinned clumps.

Table 2.--Mean height growth of surviving crop stems

	1958-1963	1964-1969	1970-1975	1958-1975
	- - - - - - - - - - Feet - - - - - - - - - -			
Poor site				
Thinned	12	8	7	27
Unthinned	13	12	8	33
Good site				
Thinned	25	16	11	52
Unthinned	23	16	12	51

Table 3.--Mean diameter growth of selected crop trees

	1958-1963	1964-1969	1970-1975	1958-1975
	- - - - - - - - - Inches - - - - - - - - -			
Poor site				
Thinned	2.4	0.9	0.9	4.2
Unthinned	2.2	1.6	1.4	5.2
Good site				
Thinned	3.6	1.7	1.6	6.9
Unthinned	3.5	1.5	1.4	6.4

SURVIVAL OF CROP TREES

McCarthy remarked that yellow-poplar stump sprouts are poor risks for future crop trees because "... they are subject to serious if not disastrous damage from wind and sleet, since the young stumps from which they spring decay very rapidly and afford them little support."[3] Excessive losses did not occur in the present study. Survival after 24 years averaged 87 percent overall. The unthinned clumps were tallied as surviving if there was one live stem, whether or not it was the crop tree designated at age 6. Thus, survival was somewhat better for the unthinned clumps than for thinned clumps (93 percent vs. 80 percent). Wendel (see footnote 1) reported similiar results; 91 percent of the stumps with sprouts at age 1 still had one or more viable sprouts at age 10.

Mortality was unrelated to parent stump size. The average stump size for clumps that died differed little from the overall average for stump size. Complete mortality of clumps occurred over the full range of stump sizes from 4 to 32 inches.

DEVELOPMENT OF UNTHINNED CLUMPS

At age 6 there was an average of 6.4 stems per unthinned sprout clumps on both sites, with a range of 2 to 14 stems per stump. Eighteen years later, at age 24, only 2.1 stems per stump remained alive. No stump had more than four live stems remaining.

Based on the relative size and vigor of the surviving stems, it appears that a natural thinning will continue. It is estimated that about 65 percent of the unthinned clumps will eventually contain only one stem, 25 percent will have two stems, and the remaining 10 percent will produce three codominant trees per parent stump.

POTENTIAL FOR BUTT ROT OF CROP TREES

One question that always arises with respect to trees of stump-sprout origin is whether or not they will contact butt rot. Yellow-poplar sprouts may become infected by butt rot fungi through the parent stump and/or through death or removal of inferior noncrop stems by suppression or thinning.[4] From visual inspection of each of the 24-year-old crop trees, it appeared that about 50 percent had not contacted butt rot from the parent stump and were unlikely to do so, because the stumps had completely rotted away and no longer served as open infection courts. In many instances there was little or no evidence that the tree originated as a stump sprout (fig. 1). The other half of the crop trees

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[3] McCarthy, E. F. 1933. Yellow-poplar characteristics, growth and management. p. 18. U.S. Dep. Agric. Tech. Bull. 356.

[4] True, R. P., and E. H. Tryon. 1966. Butt decay in yellow-poplar sprouts in West Virginia. W. Va. Univ. Agric. Exp. Stn. Bull. 541-T, 66 p.

contained open infection courts from the decaying parent stump, ranging from small holes at the base to large segments of decaying stumps (fig. 2).

There appeared to be no difference in decay potential between crop trees in thinned and unthinned clumps. There was, however, a tendency for greater rot potential from the larger stumps and in the less vigorous stems. Sprouts

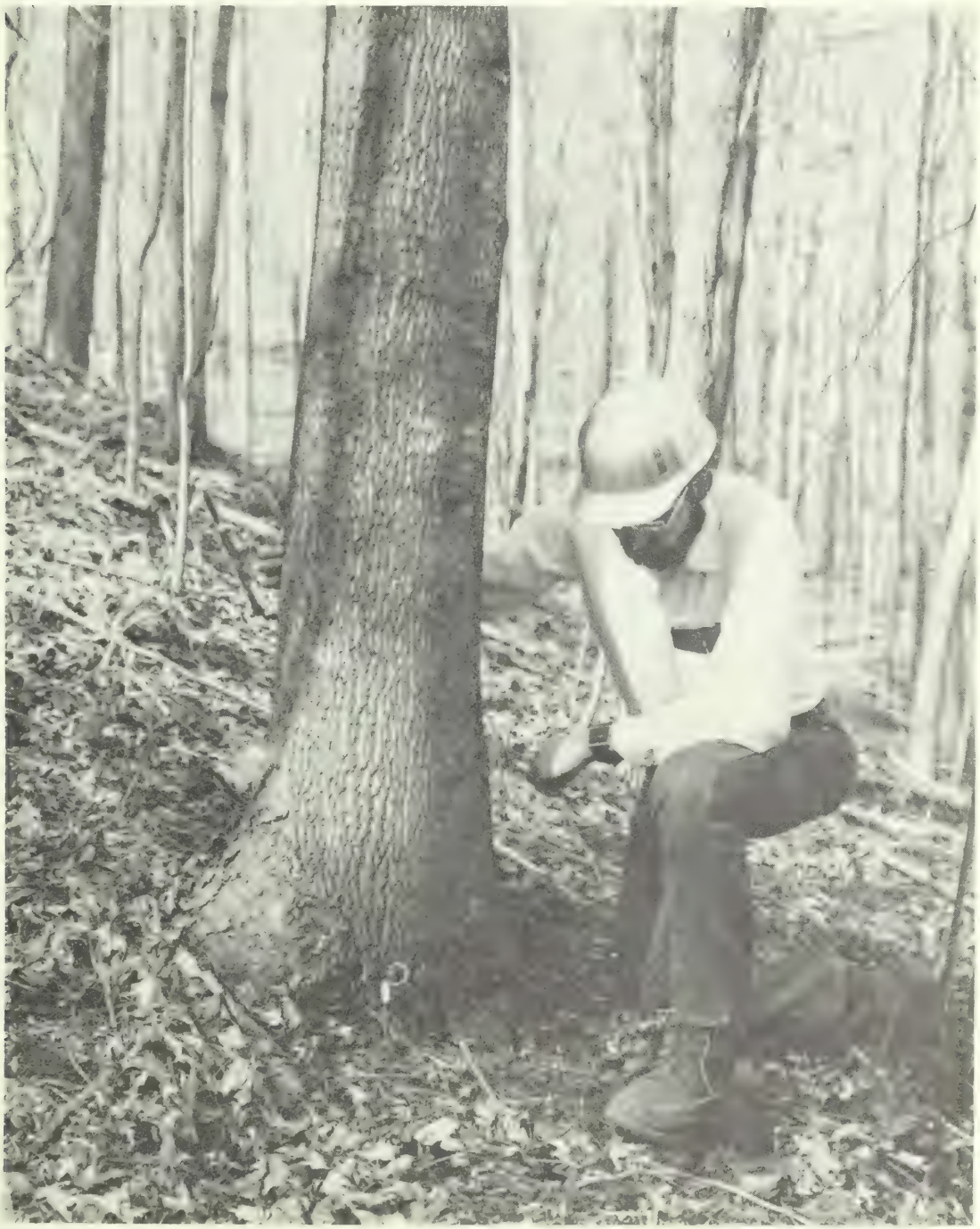

Figure 1.--All evidence of the 8-inch parent stump has been obliterated by this 24-year-old stump sprout. Tree is 11.8 inches d.b.h. and 78 feet tall.

from the larger stumps apparently are more susceptible to rot due to the slower decay of the parent stumps. A majority of crop trees with large, open infection courts (fig. 2), originated from stumps over 15 inches in diameter. Clumps on the poor site and those suppressed by residuals had more crop trees with open infection courts than did the vigorously growing trees on the good site.

Figure 2.--A decaying, 18-inch stump still serves as open infection court for butt rot in a 24-year-old sprout. Tree is 9.0 inches d.b.h. and 79 feet tall.

In addition to the hazard of butt rot from decaying parent stumps, crop trees in the unthinned clumps are susceptible to decay from dying ancillary stems. Overall, about 55 percent of the crop trees in unthinned clumps had dead stubs or dying ancillary stems which could serve as infection courts before the trees reach large sawtimber size (fig. 3). It is not known to what extent decay will result or the extent of damage from decay, only that the potential

Figure 3.--A 24-year-old sprout clump which originated from an 18-inch stump. Small stem on right is dead, and small stem on left will probably not survive to rotation end. Both can provide entry for butt rot fungi into the elite stem, which is 9.2 inches d.b.h. and 84 feet tall.

for decay exists. In other cases of multiple stems, the trees were of nearly equal size and appeared likely to survive (fig. 4). In cases like these, the potential for rot is small if twin sprouts are treated as one and are either cut or left together.

Figure 4.--Twin stems from 8-inch stump at 24 years of age. Stem on right is 12.2 inches d.b.h. and 87 feet tall. Stem on left is 12.0 inches d.b.h. and 88 feet tall. These stems should be treated as one and either both removed in thinning or both carried to rotation.

SUMMARY AND CONCLUSIONS

Stumps of yellow-poplar sprout profusely after harvest of mature, second-growth stands. One or more of these sprouts on each stump are usually capable of very rapid height and diameter growth. On the good site in this study, the best crop tree on each stump averaged 80 feet tall and 9.6 inches d.b.h. at 24 years of age. Some sprouts were over 90 feet tall and nearly 14 inches in diameter.

Thinning to one stem per stump at 6 years of age did not affect either height or diameter growth over the succeeding 18 years. Yellow-poplar sprout clumps in this and other studies have demonstrated outstanding ability to thin themselves. At age 6 there were approximately six stems per stump, and by age 24 the unthinned clumps contained an average of 2.1 stems per clump. No stump had more than four surviving sprouts at 24 years of age. As a result of the rapid and almost complete natural thinning, it is not necessary to thin artificially to encourage growth of crop trees.

Early precommercial thinning with yellow-poplar sprout clumps has been recommended to reduce incidence of butt rot by (1) favoring low-origin stems, (2) eliminating all sprouts from large stumps, and (3) reducing clumps originating from small stumps to one stem prior to heartwood formation in the sprouts (see footnote 4).

From the results of the present study, it appears that thinning to the one best low-origin stem at an early age will have little effect on incidence of butt-log rot caused by the parent stump. About half the crop trees in this study had open infection courts resulting from decaying parent stumps. True (see footnote 2) reported that 80 percent of the sprouts arise at the soil line. Furthermore, this and other studies indicate that low-origin sprouts survive better than high-origin sprouts, which are subject to breakage. As a result, the stem(s) which dominate a sprout clump will probably be of low origin, whether or not they are artificially thinned.

This study shows that the greatest incidence of rot occured on the largest stumps--particularly those over 15 inches in diameter. Thus, elimination of all sprouts from large stumps will reduce the incidence of butt rot in crop trees. Ancillary stems dying after heartwood has formed in them (fig. 3) can introduce rot into the dominant crop tree. Thinning to one stem on small stumps at an early age is a valid strategy for reducing chances of rot.

On the other hand, this research indicates that waiting until a commercial thinning can be made is an important option to consider. At 24 years of age the majority of the stump sprouts on the good site are of pulpwood size, and some are even small saw-log size. Poor-risk stump sprouts can probably be removed at this point on a break-even basis, if not a profit. Sound stems of stump-sprout origin (about 50 percent of all stump sprouts in this study) and stems of seedling and seedling sprout origin should provide sufficient crop trees.

Beck, Donald E.
1977. Growth and development of thinned versus unthinned yellow-poplar sprout clumps. USDA For. Serv. Res. Pap. SE-173, 11 p. Southeast. For. Exp. Stn., Asheville, N. C.

Yellow-poplar stump sprouts are capable of very rapid growth and often dominate stands on good sites following harvest cutting. Thinning to one stem per stump at 6 years of age did not affect either height or diameter growth over the succeeding 18 years. The untreated clumps thinned themselves to an average of two stems per clump during the same time period. Thinning to one stem had no apparent effect on butt rot potential from the parent stump, but did reduce the potential for rot from dying ancillary stems.

Keywords: Height growth, diameter growth, butt rot, mortality, fungi, multiple stems, stumps.

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Predicting Fire Behavior in Palmetto-Gallberry Fuel Complexes

by

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and
F. A. Albini

U.S. Department of Agriculture-Forest Service
Southeastern Forest Experiment Station

January 1978

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Predicting Fire Behavior in Palmetto-Gallberry Fuel Complexes

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Abstract.--Rate of spread, fireline intensity, and flame length can be predicted with reasonable accuracy for backfires and low-intensity head fires in the palmetto-gallberry fuel complex of the South. This fuel complex was characterized and variables were adjusted for use in Rothermel's (1972) spread model.

Age of rough, height of understory, percent of area covered by palmetto, basal area of overstory, season of year, moisture content of dead fuels, and midflame windspeed must be known to make predictions. These fire behavior predictions do not apply to high-intensity wildfires where spotting and crowning are occurring.

Keywords: Rate of spread, fireline intensity, flame length, prescribed burning.

Firefighters need to know how fast a fire will spread, how hot it will burn, and what the flame length will be. Prescribed burners need the same information to plan for fireline placement and burnout time, and to keep damage of overstory trees to a minimum. Rate of spread is also needed to estimate smoke production and transport, which are critical factors in smoke management (Southern Forest Fire Laboratory Staff 1976). The mathematical model of fire behavior developed by Rothermel (1972) predicts fire spread and intensity well enough if the fuel is relatively homogeneous. It is difficult to adequately characterize a heterogeneous fuel complex like the palmetto-gallberry type. The purpose of the research described here, therefore, was to characterize the palmetto-gallberry fuel complex and then adjust several variables, such as fuel depth and moisture content of extinction, so that the output of Rothermel's model was representative of measured fire behavior.

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[1] Formerly located at Southeastern Forest Experiment Station, Southern Forest Fire Laboratory, Macon, Ga.

[2] Stationed at the Northern Forest Fire Laboratory, Missoula, Mont.

This fuel type is the complex association of saw-palmetto [Serenoa repens (Bartr.) Small] and common gallberry [Ilex glabra (L.) Gray] with many other plants beneath slash pines (Pinus elliottii Engelm.) or mixtures of slash and longleaf pine (P. palustris Mill.). Openings frequently contain small shrubs [Vaccinium spp., Quercus spp., and Kalmiella hirsuta (Walt.) Small] and wiregrass (Aristida spp.). Palmetto and gallberry are two of the most common plants occurring in forest understories on the Lower Coastal Plain of the Southern United States. In this area, live and dead fuels accumulate so rapidly that a wildfire in a 5-year accumulation can seriously damage or kill the pine overstory, even though the pines are fire resistant. To preclude destructive wildfires, burning is often prescribed for hazard reduction.

Throughout the palmetto-gallberry fuel complex, fuel height and fuel loading vary widely. Fuel height may range from 1 to 6 or more feet,[3] while loading may vary from 1 to 25 tons/acre (Bruce 1951; Sackett 1975). This variation makes it impossible to construct a single fuel model that is typical of the type. What is needed, and presented here, is a dynamic fuel model that accounts for site conditions, fuel-accumulation time, and species composition. This model permits reasonably precise prediction of fire behavior, as well as systematic analysis of the consequences of fuel treatments. Rothermel and Philpot (1973) developed a similar model for the chaparral fuel complex.

This paper is divided into two parts for the convenience of the reader. Some may be interested only in the application of the results; others may want details on the methods and procedures used to arrive at this end product. Part I provides the tables and charts needed to predict fire behavior in the palmetto-gallberry fuels; examples are provided to demonstrate the method. Part II gives the details of the research process.

Although the data and methods presented are the best available at this time, certain limitations should be clearly understood. Fire behavior predictions from the Rothermel model are for uniform wind conditions and a continuous, homogeneous fuel layer that is contiguous to the ground. No information on crown fires is presented. Windspeed, wind direction, and characteristics of the fuel layer will vary on actual fires, resulting in possible differences between estimated and actual values. Another major factor, not currently included in the fire behavior model, is the influence of spotting on fire spread and intensity. Spotting is especially important in wildfires. Even so, the predictions given here provide an estimate of fire behavior on prescribed burns and on the initial stages of wildfires. The resulting information can be incorporated in fire planning by the forest fire manager.

PART I: FIELD APPLICATION

The most efficient and accurate way to use the information presented in this paper would be to program all the fuel weight-predicting equations and fuel parameters into a computer-based model of wild land fire behavior like that described by Albini (1976a). Then, not only could all variables be entered on a continuous scale, but additional information on fire growth rate, scorch height, and a number of other factors could be obtained.

[3] Factors to convert from English units to International System of Units (SI) are listed on page 44.

Since computer terminals are not available at all locations, the results are presented in tables and curves from which reasonably accurate predictions can be made.

DATA NEEDED

Measurements that must be taken in the field have been reduced to a minimum. Those needed to predict fuel characteristics are easily measured. The items needed for predictions are:

1. Age of understory rough (yr)
2. Basal area of overstory (ft^2)
3. Average height of understory (ft)
4. Palmetto coverage (pct)
5. Season of year
6. Midflame windspeed (mi/h).

Average or visual understory height and percent palmetto coverage can be estimated by eye. The simplest method is to locate a number of 100-foot-long transects at different places in the stand. The number of feet of transect covered by palmetto fronds equals the percent palmetto. If transects are not 100 feet long, the percent coverage must be calculated. An estimate of average understory height can also be obtained along these transects. In a very dense understory, the average height is that to the top foliage of the palmetto and gallberry plants. In a scattered or patchy palmetto stand, however, it is necessary to measure heights of low shrubs or grasses that occur in the openings as well as palmetto and gallberry foliage. The average height is between these two measurements and should be weighted by the amount of coverage in each category.

Dead-fuel moisture content can be estimated using the 100-hour timelag tables in the National Fire Danger Rating System (NFDRS) (Deeming and others 1972); such information should be available at the nearest fire danger station. The windspeed needed for predictions is that in the stand that will be burned. Windspeed may be obtained from the danger station and reduced to an appropriate level using tables presented by Cooper (1965).

BACKFIRE BEHAVIOR

Nine pairs of tables predicting fire behavior are presented. In each pair, the one on the left-hand page predicts flame length for backfires or for fires without wind. The one on the right-hand page shows the rate of spread in feet per minute under the same conditions. Your first problem is to determine which pair of tables applies to your conditions. This decision must be based upon the basal area of the tree overstory and the percentage of area covered by palmetto:

Table numbers	Overstory basal area[4]	Palmetto coverage[5]
1, 2	low	sparse
3, 4	low	broken
5, 6	low	continuous
7, 8	medium	sparse
9, 10	medium	broken
11, 12	medium	continuous
13, 14	high	sparse
15, 16	high	broken
17, 18	high	continuous

Once the proper table is selected, it is a simple matter to locate the predicted flame length or spread rate from the age of rough, the dead-fuel moisture content, the height of understory, and the season of year (summer or winter).

WIND ADJUSTMENTS

The values in these tables are for calm conditions or for backfires. With heading fires, adjustments must be made for wind effects. These adjustments can be estimated with the help of tables 19-21 and figures 1 and 2. The proper table to use depends upon overstory density:

Table number	Overstory basal area[6]
19	low
20	medium
21	high

These tables show letter designations for fuel categories. Once the proper letter for your fuel condition has been found, enter figure 1 to determine the effect of wind on rate of spread and figure 2 to determine the effect of wind on flame length. The values found in these figures should be multiplied by the values obtained for backfires in tables 1-18.

FIRE INTENSITY

From flame length, determined in figure 2, fire intensity can be determined. This relationship is illustrated in figure 3, which shows fire intensities in British thermal units per second per foot (Btu/s/ft). This figure also shows

[4] Values of basal area (ft^2) used to generate these tables were: 30 ft^2 for low, 70 ft^2 for medium, and 110 ft^2 for high conditions.

[5] Values of palmetto coverage (percent) used to generate these tables were: 15 percent for sparse, 50 percent for broken, and 85 percent for continuous conditions.

[6] See footnote 4.

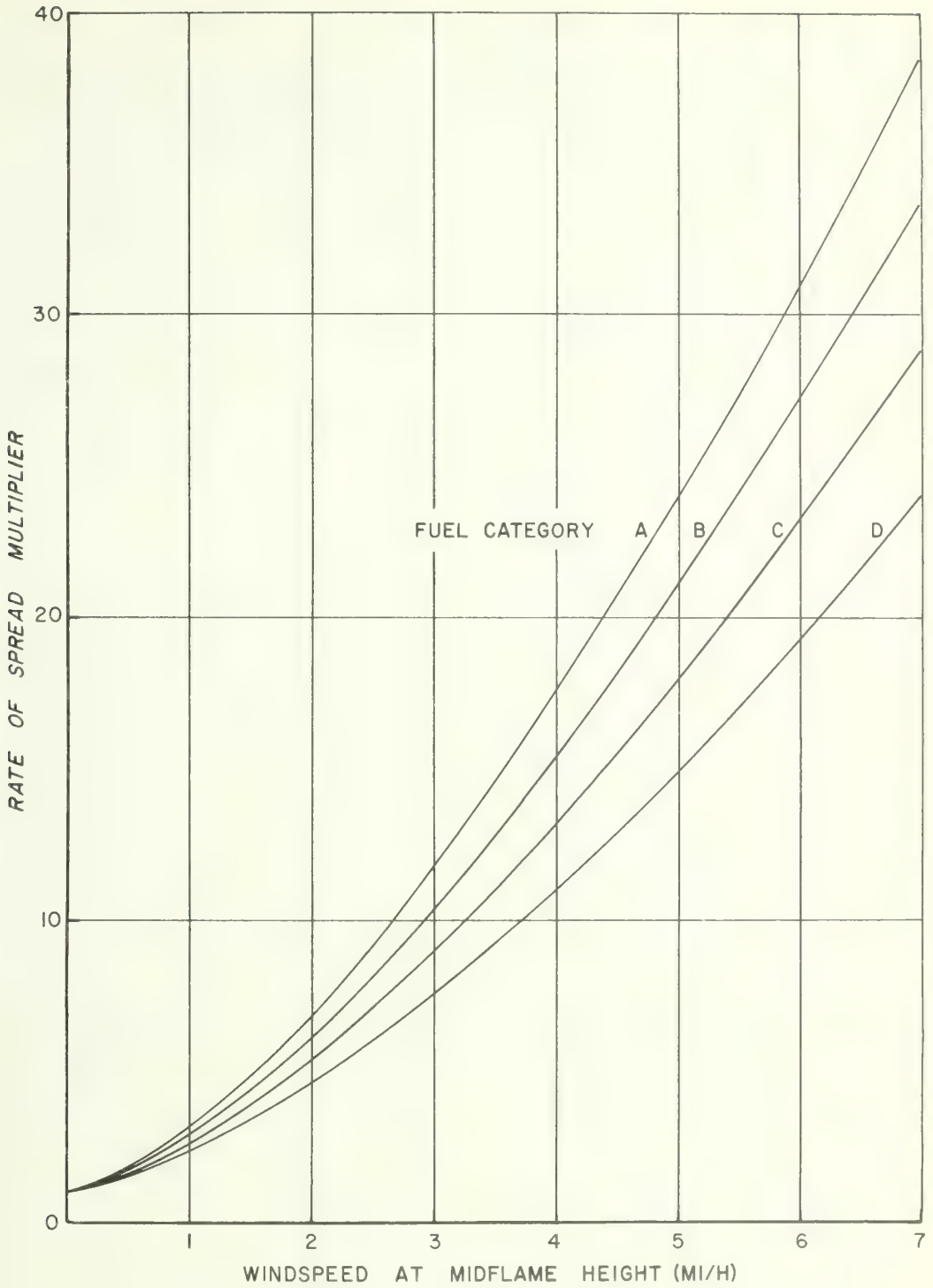

Figure 1.--Rate-of-spread multiplier for head fires.

the intensities at which spotting, loss of control, and crowning often begin. Intensity of prescribed burns is normally below 100 Btu/s/ft. Spotting usually does not occur until intensity reaches 500 Btu/s/ft.

We have worked up some examples to familiarize you with the use of the application tables and figures 1-3. After you have tried these examples, you should have little trouble in making predictions for your own conditions.

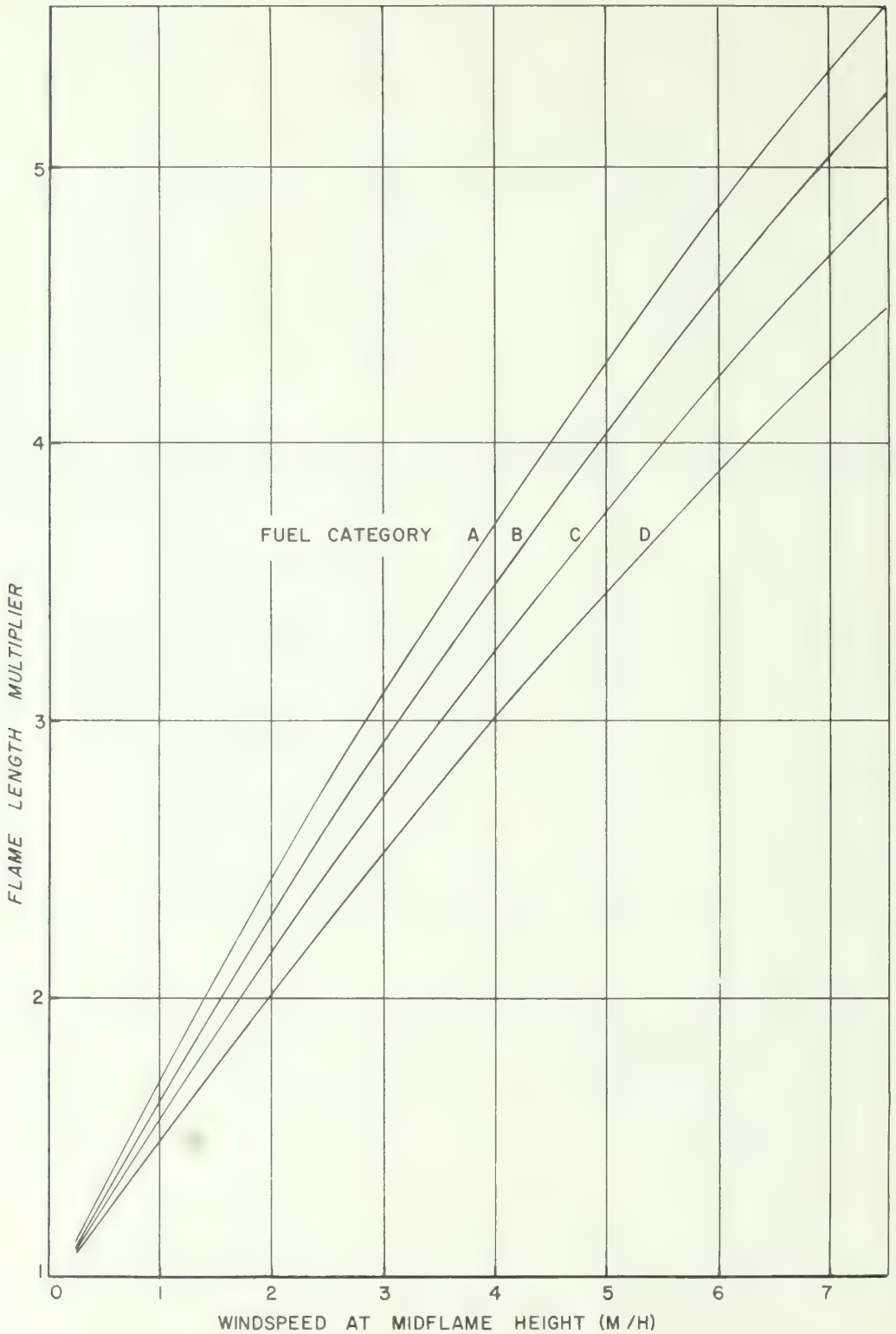

Figure 2.--Flame-length multiplier for head fires.

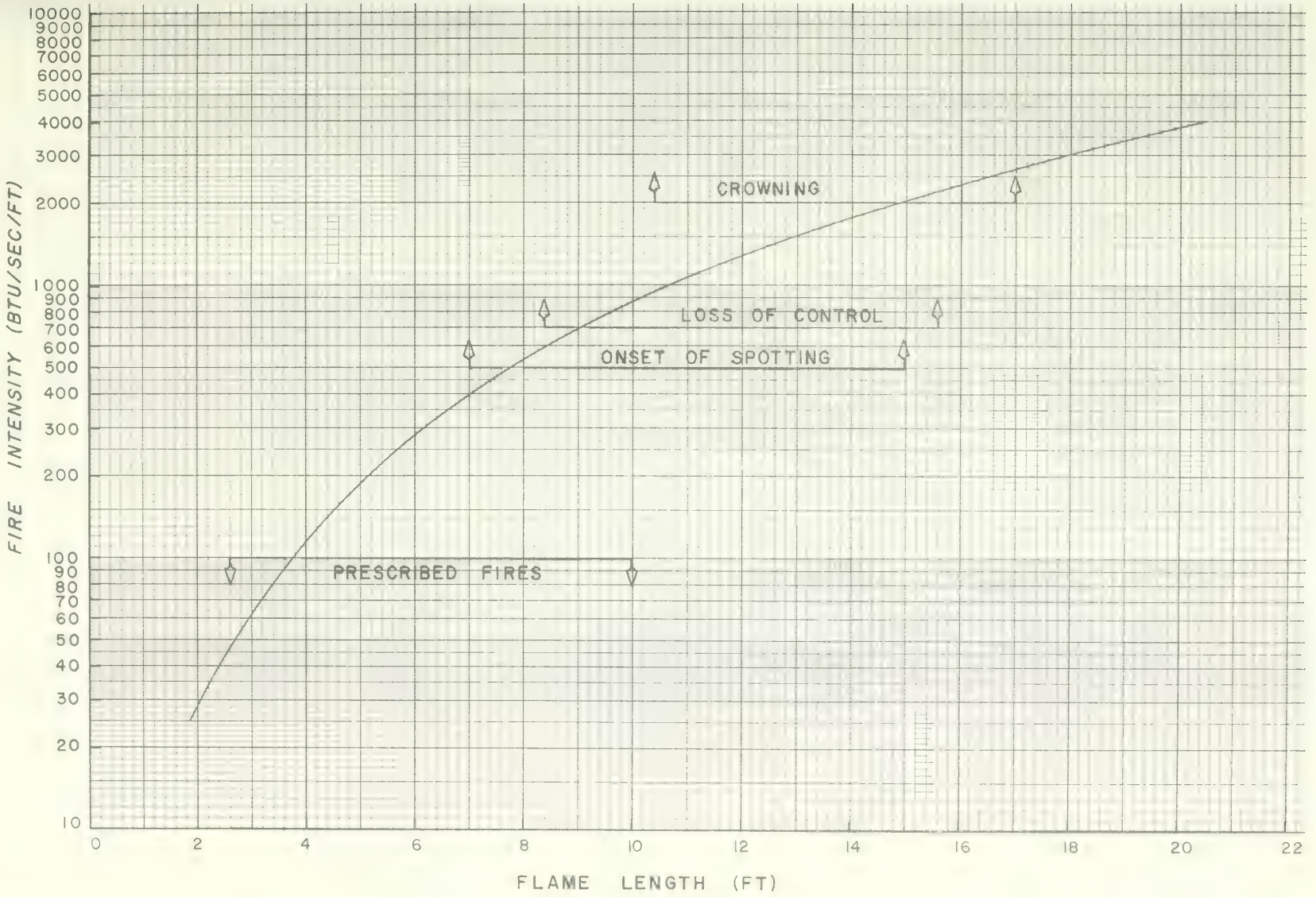

Figure 3.--Relationship between flame length and fire intensity.

Example No. 1

A land manager is planning a prescribed fire in a stand of slash pine that has a 6-year-old palmetto-gallberry understory. The stand conditions have been measured as follows: basal area of 65 ft^2/acre, understory fuel height of $3\frac{1}{2}$ feet, and a coverage of palmetto of 60 percent. Because of the age of rough, he will use a winter backfire; therefore, the wind factors will not be determined for this case. Because this is a planning situation, the values entered in the tables will be rounded to the closest available figures.

The first step is to locate the table that corresponds to basal area of 65 (in this case rounded to 70). After finding this table, the age is located on the left-hand column; tabular age 5 is used because it is closest to the acutal value. Next, find the height of the understory which is shown across the top of the page. The height of $3\frac{1}{2}$ feet falls midway between the values presented in the table. Since rates of spread are very similar for the two heights in question, it makes little difference which column is used. Selecting the column marked "4 feet" and the group of figures under "winter," the rate-of-spread values are seen to range from 0.72 ft/min for moisture contents of 30 percent to a value of 2.4 ft/min for a fuel moisture of 5 percent.

The fuel moisture content at the time of burning would be between these extremes and probably between 10 to 20 percent, resulting in a fairly narrow range in spread rates that need to be considered. Planning the location of interior firelines could be made based on these figures, without knowing the exact moisture content that might occur at the time of burn. An estimate of flame length could also be obtained for this burn by following the same procedures and entering the flame-length tables. Once flame length has been estimated, it would also be possible to estimate fire intensity.

Example No. 2

A fire control officer would like an estimate of initial wildfire behavior during the spring fire season in two different palmetto-gallberry stands. Stand I has recently been burned (2 years ago), is sparsely populated by palmetto, and has an average understory height of 2 feet. Stand II has an old rough (13 years since last disturbance), a fairly dense palmetto cover, and an understory height of 5 feet. It is assumed that the dead-fuel moisture content will be low, about 5 percent, and that the windspeed will be 6 mi/h within the stand. For simplification, assume both stands have the same basal area, 75 ft^2/acre.

Again, the first step is to find the backfire rate-of-spread table with basal area and palmetto values closest to the measured values. Basal area 70 and "sparse" palmetto coverage should be used for Stand I. In this table, find the column for winter and an understory height of 2 feet. Follow down this column to the row for age 2 and a 5 percent moisture content for dead fuel. Rate of spread is found to be 2.8 ft/min. For Stand II, use the table for basal area 70 and "continuous" palmetto coverage. Enter the column for winter and an understory height of 5 feet; go down to age 15 and a moisture content of 5 percent. Estimated rate of spread is 2.9 ft/min.

Now, entering the wind-effect category table for basal area 70, percent palmetto 15 (sparse), height of 2 and age of 2, we find Stand I falls in category B. For Stand II, we also enter the table headed by basal area 70, but the section headed percent palmetto 85 is used. Next, find the age of 15 in the left-hand column and look across until you reach height 5; this gives a category C.

Turning to figure 1, we find a set of curves from which we will obtain our head fire rate of spread multiplier. We enter a windspeed of 6 mi/h and read the value at the intersection with curve B. For Stand I, we get a factor of 27.0. This value is multiplied by the zero-wind rate of spread and gives us a head fire rate of spread of 76 ft/min. Again entering the curve at 6 mi/h windspeed, we find the factor of 23.1 for wind-effect category C. Using this value multiplied by the zero-wind rate of spread, we find the head fire rate of spread in Stand II will be 67 ft/min.

The young understory fuel conditions produce a higher spread rate than the older understory. However, if we enter the flame-length tables following the rate-of-spread procedures, we find a 2.1-foot flame, at zero windspeed, for Stand I and a 3.5-foot flame for Stand II. The wind-effect category does not change, so by entering figure 2 we find the multiplier for flame length. Again entering the graph at 6 mi/h windspeed, we find a factor for curve B of 4.56 and a factor for curve C of 4.24. Multiplying these values times zero-windspeed flame length, we find that the flame length in the young, open stand will be 9.6 feet, while the flame length in the older, heavier fuel will be 14.9 feet. Stand II has a flame $1\frac{1}{2}$ times longer than Stand I. Using figure 3, it is possible to estimate fire intensity. The fire in Stand I would have an intensity of 780 Btu/s/ft, while in Stand II it would be 2,000 Btu/s/ft. Spotting would probably occur on both fires, but crowning would be much more likely in the stand with heavy accumulations of saw palmetto.

As presented in these examples, the fire behavior occurring under different conditions can be assessed. The information is probably most useful in the planning stages, not only for preparing prescribed burn plans, but also to provide presuppression planners a systematic way to note differences that stand age and fuel buildup have on fire behavior factors. Also, if windspeed within the stand and moisture content of the dead fuel are known, real-time estimates of rate of spread could be made.

Table 1.--Predicted flame lengths in palmetto-gallberry fuel type where overstory density is 30 ft^2/acre (low) and percent palmetto coverage is 15 percent (sparse)

Age of rough (years)	Dead-fuel moisture	Height of understory (feet)											
		1		2		3		4		5		6	
		Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter
	Percent	Feet											
	5	1.2	1.3	1.3	1.4	1.3	1.4	1.3	1.4	1.3	1.5	1.1	1.6
	10	1.0	1.0	1.1	1.1	1.1	1.2	1.1	1.2	.99	1.3	.53	1.1
1	15	.88	.92	.97	1.0	1.0	1.1	.98	1.1	.51	1.0	.49	.52
	20	.82	.85	.91	.96	.95	1.0	.53	.97	.49	.52	.47	.50
	30	.65	.67	.69	.77	.48	.51	.43	.46	.40	.42	.38	.41
	5	1.4	1.5	1.5	1.6	1.5	1.6	1.5	1.6	1.6	1.7	1.6	1.9
	10	1.2	1.2	1.3	1.4	1.3	1.4	1.3	1.4	1.4	1.5	1.1	1.6
2	15	1.0	1.1	1.2	1.2	1.2	1.3	1.2	1.3	1.0	1.4	.60	1.1
	20	.95	.99	1.1	1.1	1.1	1.2	1.0	1.3	.61	.96	.58	.62
	30	.75	.77	.86	.91	.60	.69	.54	.57	.50	.53	.47	.51
	5	1.4	1.5	1.6	1.7	1.6	1.7	1.6	1.7	1.7	1.8	1.7	1.9
	10	1.2	1.2	1.3	1.4	1.4	1.5	1.4	1.5	1.4	1.6	1.2	1.7
3	15	1.1	1.1	1.2	1.3	1.2	1.3	1.3	1.4	1.1	1.5	.64	1.3
	20	.98	1.0	1.1	1.2	1.2	1.3	1.1	1.3	.65	1.1	.61	.65
	30	.78	.80	.89	.95	.62	.74	.57	.60	.53	.56	.50	.54
	5	1.4	1.5	1.6	1.7	1.6	1.7	1.6	1.8	1.7	1.8	1.7	2.0
	10	1.2	1.3	1.3	1.4	1.4	1.5	1.4	1.5	1.5	1.6	1.3	1.7
4	15	1.1	1.1	1.2	1.3	1.3	1.4	1.3	1.4	1.2	1.5	.65	1.3
	20	.99	1.0	1.1	1.2	1.2	1.3	1.1	1.3	.66	1.1	.62	.67
	30	.79	.82	.88	.97	.63	.68	.58	.61	.54	.57	.51	.55
	5	1.4	1.5	1.6	1.7	1.6	1.8	1.6	1.8	1.7	1.9	1.7	2.0
	10	1.2	1.3	1.4	1.4	1.4	1.5	1.5	1.6	1.5	1.7	1.3	1.7
5	15	1.1	1.1	1.2	1.3	1.3	1.4	1.3	1.5	1.2	1.5	.66	1.3
	20	.99	1.0	1.2	1.2	1.2	1.3	1.1	1.4	.66	1.1	.63	.68
	30	.80	.83	.85	.98	.63	.66	.58	.61	.54	.58	.52	.55
	5	1.4	1.5	1.6	1.7	1.6	1.8	1.7	1.8	1.8	1.9	1.8	2.1
	10	1.2	1.3	1.4	1.5	1.4	1.5	1.5	1.6	1.5	1.7	1.2	1.8
8	15	1.1	1.1	1.2	1.3	1.3	1.4	1.4	1.5	1.1	1.5	.67	1.3
	20	1.0	1.1	1.2	1.2	1.2	1.3	1.0	1.4	.67	1.0	.64	.69
	30	.78	.85	.64	.92	.62	.65	.58	.62	.55	.58	.53	.56
	5	1.3	1.4	1.5	1.7	1.6	1.8	1.7	1.9	1.8	2.0	1.8	2.2
	10	1.1	1.2	1.3	1.4	1.5	1.6	1.5	1.7	1.5	1.8	1.1	1.8
15	15	1.0	1.1	1.2	1.3	1.3	1.4	1.3	1.6	.90	1.6	.67	1.2
	20	.97	1.0	1.2	1.3	1.2	1.4	.69	1.3	.67	.71	.65	.69
	30	.50	.61	.58	.61	.58	.61	.57	.60	.55	.58	.53	.57
	5	1.1	1.2	1.5	1.6	1.7	1.8	1.8	1.9	1.9	2.1	1.8	2.3
	10	1.0	1.1	1.3	1.4	1.5	1.6	1.6	1.8	1.5	1.9	1.1	1.9
25	15	.93	.99	1.2	1.3	1.3	1.5	1.2	1.6	.67	1.6	.66	1.1
	20	.85	.95	1.0	1.2	.89	1.3	.65	1.2	.64	.69	.64	.68
	30	.40	.42	.50	.53	.53	.56	.53	.57	.53	.56	.52	.56

Table 2.--Predicted rate of spread in palmetto-gallberry fuel type where overstory density is 30 ft^2/acre (low) and percent palmetto coverage is 15 percent (sparse)

Age of rough (years)	Dead-fuel moisture	Height of understory (feet)											
		1		2		3		4		5		6	
		Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter
	Percent	Feet/minute											
1	5	1.5	1.6	1.7	1.9	1.5	1.7	1.2	1.5	1.1	1.4	.75	1.3
	10	1.1	1.2	1.4	1.5	1.2	1.4	1.1	1.3	.79	1.2	.36	.88
	15	.97	1.0	1.2	1.3	1.1	1.3	.89	1.1	.38	.87	.32	.37
	20	.86	.92	1.1	1.2	1.0	1.2	.45	.94	.36	.41	.30	.35
	30	.62	.65	.74	.87	.47	.52	.35	.40	.28	.32	.24	.28
2	5	1.6	1.7	1.9	2.2	1.7	2.0	1.5	1.7	1.3	1.6	1.2	1.5
	10	1.2	1.3	1.5	1.7	1.4	1.6	1.3	1.5	1.1	1.4	.75	1.3
	15	1.0	1.1	1.3	1.5	1.3	1.4	1.1	1.3	.82	1.2	.41	.83
	20	.90	.97	1.2	1.3	1.2	1.3	.94	1.2	.46	.80	.39	.45
	30	.64	.68	.87	.97	.56	.69	.44	.50	.36	.41	.30	.35
3	5	1.5	1.6	1.9	2.1	1.8	2.0	1.5	1.8	1.4	1.7	1.3	1.6
	10	1.2	1.3	1.5	1.7	1.5	1.7	1.3	1.5	1.2	1.4	.88	1.4
	15	.98	1.1	1.3	1.5	1.3	1.5	1.2	1.4	.91	1.3	.43	.97
	20	.87	.95	1.2	1.3	1.2	1.3	1.0	1.3	.48	.93	.41	.47
	30	.63	.67	.86	.97	.57	.72	.46	.52	.38	.43	.32	.37
4	5	1.4	1.6	1.8	2.1	1.7	2.0	1.5	1.8	1.4	1.7	1.3	1.6
	10	1.1	1.2	1.5	1.7	1.4	1.7	1.3	1.5	1.2	1.5	.90	1.4
	15	.94	1.0	1.3	1.4	1.3	1.5	1.2	1.4	.93	1.3	.44	1.0
	20	.84	.92	1.2	1.3	1.2	1.3	.99	1.3	.49	.94	.41	.48
	30	.62	.66	.83	.95	.56	.64	.46	.52	.38	.44	.33	.38
5	5	1.3	1.5	1.8	2.0	1.7	2.0	1.5	1.8	1.4	1.7	1.3	1.6
	10	1.1	1.2	1.4	1.6	1.4	1.6	1.3	1.5	1.2	1.5	.90	1.4
	15	.90	1.0	1.2	1.4	1.3	1.4	1.2	1.4	.91	1.3	.44	1.0
	20	.81	.89	1.1	1.3	1.2	1.3	.96	1.3	.49	.92	.42	.48
	30	.60	.64	.77	.93	.54	.60	.45	.51	.38	.43	.33	.38
8	5	1.2	1.3	1.6	1.9	1.6	1.8	1.5	1.7	1.4	1.7	1.3	1.6
	10	.94	1.1	1.3	1.5	1.3	1.5	1.3	1.5	1.2	1.5	.84	1.4
	15	.81	.91	1.2	1.3	1.2	1.4	1.1	1.4	.82	1.3	.44	.93
	20	.73	.81	1.1	1.2	1.1	1.3	.83	1.2	.48	.79	.41	.48
	30	.53	.61	.52	.81	.50	.55	.43	.49	.37	.43	.33	.38
15	5	.82	.94	1.2	1.4	1.3	1.5	1.3	1.6	1.3	1.6	1.2	1.6
	10	.67	.77	.99	1.1	1.1	1.3	1.2	1.4	1.1	1.4	.72	1.3
	15	.60	.68	.89	1.0	1.0	1.2	.97	1.2	.60	1.2	.41	.80
	20	.55	.62	.82	.94	.85	1.1	.47	1.0	.43	.49	.39	.45
	30	.26	.34	.37	.41	.39	.44	.37	.42	.34	.38	.31	.35
25	5	.52	.61	.84	.98	1.0	1.2	1.1	1.3	1.2	1.4	1.1	1.5
	10	.44	.51	.72	.84	.89	1.0	.96	1.2	.91	1.2	.61	1.2
	15	.40	.46	.65	.77	.78	.95	.73	1.0	.37	1.0	.36	.68
	20	.36	.43	.55	.70	.50	.83	.36	.74	.35	.41	.34	.39
	30	.15	.17	.24	.27	.28	.32	.29	.33	.28	.32	.27	.31

Table 3.--Predicted flame lengths in palmetto-gallberry fuel type where overstory density is 30 ft^2/acre (low) and palmetto coverage is 50 percent (broken)

Age of rough (years)	Dead-fuel moisture	Height of understory (feet)											
		1		2		3		4		5		6	
		Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter
	Percent	Feet											
1	5	1.2	1.3	1.3	1.4	1.4	1.5	1.4	1.5	1.4	1.6	.91	1.6
	10	1.0	1.1	1.2	1.2	1.2	1.3	1.2	1.4	.83	1.4	.57	1.0
	15	.92	.98	1.1	1.1	1.1	1.2	.84	1.2	.54	.84	.52	.55
	20	.87	.92	1.0	1.1	.87	1.1	.55	.75	.52	.55	.50	.53
	30	.48	.67	.51	.54	.49	.52	.45	.48	.42	.45	.41	.44
2	5	1.4	1.5	1.6	1.7	1.7	1.8	1.7	1.8	1.7	1.9	1.7	2.0
	10	1.2	1.3	1.4	1.5	1.4	1.5	1.5	1.6	1.4	1.7	.98	1.7
	15	1.1	1.1	1.3	1.3	1.3	1.4	1.3	1.5	.89	1.5	.65	1.0
	20	1.0	1.1	1.2	1.3	1.2	1.4	.86	1.3	.66	.71	.62	.67
	30	.74	.86	.63	.83	.62	.65	.57	.61	.54	.57	.51	.55
3	5	1.5	1.6	1.7	1.8	1.8	1.9	1.8	1.9	1.8	2.0	1.8	2.1
	10	1.2	1.3	1.4	1.6	1.5	1.6	1.6	1.7	1.6	1.8	1.3	1.8
	15	1.1	1.2	1.3	1.4	1.4	1.5	1.4	1.6	1.1	1.6	.70	1.3
	20	1.1	1.1	1.3	1.3	1.3	1.4	1.1	1.4	.71	1.0	.67	.72
	30	.78	.90	.67	.91	.66	.69	.62	.65	.58	.61	.55	.59
4	5	1.5	1.6	1.7	1.9	1.8	1.9	1.8	2.0	1.9	2.1	1.9	2.2
	10	1.3	1.4	1.5	1.6	1.6	1.7	1.6	1.8	1.6	1.9	1.4	1.9
	15	1.1	1.2	1.4	1.4	1.4	1.5	1.5	1.6	1.2	1.7	.73	1.4
	20	1.1	1.1	1.3	1.4	1.4	1.5	1.1	1.5	.73	1.1	.70	.74
	30	.77	.91	.68	.92	.67	.71	.63	.67	.60	.64	.57	.61
5	5	1.5	1.6	1.8	1.9	1.8	2.0	1.9	2.0	1.9	2.1	2.0	2.2
	10	1.3	1.4	1.5	1.6	1.6	1.7	1.7	1.8	1.7	1.9	1.4	2.0
	15	1.2	1.2	1.4	1.5	1.5	1.6	1.5	1.7	1.3	1.7	.74	1.5
	20	1.1	1.2	1.3	1.4	1.4	1.5	1.2	1.5	.75	1.2	.71	.76
	30	.75	.92	.69	.90	.68	.72	.65	.68	.61	.65	.58	.62
8	5	1.5	1.6	1.8	2.0	1.9	2.1	2.0	2.1	2.0	2.2	2.1	2.4
	10	1.3	1.4	1.6	1.7	1.7	1.8	1.7	1.9	1.8	2.0	1.6	2.1
	15	1.2	1.3	1.4	1.5	1.5	1.6	1.6	1.7	1.3	1.8	.78	1.6
	20	1.1	1.2	1.4	1.5	1.4	1.6	1.2	1.6	.78	1.3	.75	.80
	30	.61	.89	.70	.75	.70	.73	.67	.71	.64	.68	.61	.65
15	5	1.5	1.6	1.8	2.0	2.0	2.1	2.1	2.3	2.2	2.4	2.2	2.5
	10	1.3	1.4	1.6	1.7	1.7	1.9	1.8	2.0	1.9	2.1	1.7	2.2
	15	1.2	1.3	1.5	1.6	1.6	1.7	1.6	1.9	1.4	1.9	.83	1.8
	20	1.1	1.2	1.4	1.5	1.4	1.6	1.1	1.7	.82	1.3	.79	.85
	30	.57	.60	.68	.72	.70	.74	.69	.73	.67	.71	.65	.70
25	5	1.3	1.5	1.8	1.9	2.0	2.2	2.2	2.4	2.3	2.5	2.4	2.7
	10	1.2	1.3	1.6	1.7	1.8	1.9	1.9	2.1	2.0	2.3	1.9	2.4
	15	1.1	1.2	1.5	1.6	1.6	1.8	1.7	2.0	1.5	2.0	.86	1.9
	20	1.0	1.1	1.3	1.5	1.3	1.7	.92	1.7	.84	1.3	.82	.88
	30	.48	.51	.63	.67	.68	.72	.69	.73	.68	.73	.67	.72

Table 4.--Predicted rate of spread in palmetto-gallberry fuel type where overstory density is 30 ft^2/acre (low) and palmetto coverage is 50 percent (broken)

Age of rough (years)	Dead-fuel moisture	Height of understory (feet)											
		1		2		3		4		5		6	
		Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter
	Percent	Feet/minute											
1	5	1.1	1.2	1.4	1.6	1.4	1.6	1.3	1.5	1.1	1.4	.63	1.3
	10	.86	.98	1.2	1.3	1.2	1.4	1.0	1.3	.62	1.2	.37	.77
	15	.76	.85	1.0	1.2	1.1	1.3	.71	1.1	.39	.68	.33	.39
	20	.70	.78	.96	1.1	.81	1.1	.44	.65	.36	.42	.32	.37
	30	.35	.52	.45	.50	.42	.47	.34	.39	.29	.33	.25	.29
2	5	1.2	1.4	1.6	1.9	1.7	1.9	1.5	1.8	1.4	1.7	1.2	1.6
	10	.97	1.1	1.4	1.5	1.4	1.6	1.3	1.5	1.1	1.5	.68	1.3
	15	.84	.94	1.2	1.4	1.3	1.5	1.1	1.4	.67	1.2	.43	.74
	20	.77	.85	1.1	1.2	1.1	1.3	.71	1.2	.48	.56	.41	.47
	30	.52	.63	.53	.74	.52	.58	.44	.50	.37	.43	.32	.37
3	5	1.2	1.4	1.7	1.9	1.7	2.0	1.6	1.9	1.5	1.8	1.4	1.7
	10	.97	1.1	1.4	1.6	1.5	1.7	1.4	1.6	1.3	1.6	.89	1.5
	15	.85	.95	1.2	1.4	1.3	1.5	1.2	1.5	.87	1.4	.47	.98
	20	.77	.86	1.1	1.3	1.2	1.4	.87	1.3	.51	.82	.44	.51
	30	.52	.64	.54	.80	.54	.60	.47	.53	.40	.46	.35	.40
4	5	1.2	1.4	1.7	1.9	1.7	2.0	1.6	1.9	1.5	1.8	1.4	1.8
	10	.96	1.1	1.4	1.6	1.5	1.7	1.4	1.6	1.3	1.6	.97	1.5
	15	.83	.94	1.2	1.4	1.3	1.5	1.2	1.5	.93	1.4	.48	1.1
	20	.76	.85	1.1	1.3	1.2	1.4	.92	1.3	.53	.90	.46	.53
	30	.50	.63	.54	.78	.54	.60	.48	.54	.41	.47	.36	.41
5	5	1.2	1.3	1.7	1.9	1.7	2.0	1.7	1.9	1.6	1.9	1.4	1.8
	10	.94	1.1	1.4	1.6	1.5	1.7	1.4	1.7	1.3	1.6	1.0	1.5
	15	.82	.92	1.2	1.4	1.3	1.5	1.3	1.5	.96	1.4	.49	1.1
	20	.75	.83	1.1	1.3	1.2	1.4	.93	1.3	.53	.94	.46	.54
	30	.47	.61	.53	.74	.54	.60	.48	.54	.42	.48	.37	.42
8	5	1.1	1.2	1.6	1.8	1.7	2.0	1.7	1.9	1.6	1.9	1.5	1.9
	10	.88	1.0	1.3	1.5	1.4	1.6	1.4	1.7	1.3	1.6	1.1	1.6
	15	.77	.88	1.2	1.3	1.3	1.5	1.3	1.5	.99	1.5	.51	1.2
	20	.71	.80	1.1	1.2	1.2	1.4	.90	1.3	.54	.98	.48	.55
	30	.35	.55	.50	.57	.52	.58	.47	.54	.42	.48	.38	.43
15	5	.87	1.0	1.3	1.5	1.5	1.8	1.6	1.8	1.6	1.9	1.5	1.9
	10	.72	.83	1.1	1.3	1.3	1.5	1.4	1.6	1.3	1.6	1.1	1.6
	15	.64	.73	.99	1.1	1.2	1.3	1.2	1.4	.95	1.4	.51	1.2
	20	.60	.67	.91	1.1	1.0	1.2	.74	1.2	.52	.93	.48	.55
	30	.27	.30	.41	.45	.45	.50	.44	.50	.41	.47	.38	.44
25	5	.61	.71	1.0	1.2	1.3	1.5	1.4	1.6	1.5	1.7	1.5	1.8
	10	.52	.60	.87	1.0	1.1	1.3	1.2	1.4	1.2	1.5	1.1	1.6
	15	.47	.54	.79	.91	97	1.1	1.0	1.3	.86	1.3	.47	1.2
	20	.43	.50	.70	.84	.77	1.0	.52	1.1	.47	.83	.45	.52
	30	.18	.21	.30	.34	.35	.40	.37	.42	.37	.42	.35	.41

Table 5.--Predicted flame lengths in palmetto-gallberry fuel type where overstory density is 30 ft^2/acre (low) and palmetto coverage is 85 percent (continuous)

Age of rough (years)	Dead-fuel moisture	Height of understory (feet)											
		1		2		3		4		5		6	
		Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter
	Percent	Feet											
	5	1.3	1.4	1.5	1.7	1.6	1.8	1.7	1.8	1.6	1.9	1.3	1.9
	10	1.1	1.2	1.3	1.4	1.4	1.6	1.4	1.6	1.1	1.6	.67	1.4
1	15	1.1	1.1	1.2	1.3	1.3	1.4	1.0	1.4	.63	1.1	.61	.65
	20	.99	1.1	1.1	1.3	.91	1.3	.65	.90	.61	.65	.58	.62
	30	.50	.53	.57	.59	.56	.59	.53	.56	.50	.53	.48	.51
	5	1.6	1.7	1.9	2.0	2.0	2.1	2.0	2.2	2.1	2.3	2.1	2.4
	10	1.3	1.4	1.6	1.7	1.7	1.8	1.8	1.9	1.8	2.0	1.5	2.1
2	15	1.2	1.3	1.5	1.6	1.6	1.7	1.6	1.8	1.3	1.8	.79	1.5
	20	1.2	1.2	1.4	1.5	1.5	1.6	1.1	1.6	.79	1.2	.75	.81
	30	.62	.88	.71	.75	.72	.76	.68	.72	.65	.69	.62	.66
	5	1.7	1.8	2.0	2.2	2.1	2.3	2.2	2.3	2.2	2.4	2.3	2.5
	10	1.4	1.5	1.7	1.9	1.8	2.0	1.9	2.1	2.0	2.2	1.8	2.3
3	15	1.3	1.4	1.6	1.7	1.7	1.8	1.7	1.9	1.6	2.0	.87	1.9
	20	1.2	1.3	1.5	1.6	1.6	1.7	1.4	1.8	.88	1.6	.84	.89
	30	.68	.99	.78	.93	.79	.83	.75	.80	.72	.76	.68	.73
	5	1.7	1.9	2.1	2.3	2.2	2.4	2.3	2.4	2.3	2.5	2.4	2.6
	10	1.5	1.6	1.8	1.9	1.9	2.1	2.0	2.1	2.1	2.3	2.0	2.4
4	15	1.3	1.4	1.6	1.8	1.8	1.9	1.8	2.0	1.8	2.1	1.2	2.0
	20	1.3	1.3	1.6	1.7	1.7	1.8	1.6	1.9	.93	1.7	.89	.95
	30	.75	1.0	.81	1.0	.83	.87	.80	.84	.76	.81	.73	.77
	5	1.8	1.9	2.2	2.3	2.3	2.5	2.3	2.5	2.4	2.6	2.5	2.7
	10	1.5	1.6	1.9	2.0	2.0	2.1	2.1	2.2	2.1	2.3	2.1	2.4
5	15	1.4	1.5	1.7	1.8	1.8	2.0	1.9	2.1	1.9	2.2	1.4	2.1
	20	1.3	1.4	1.6	1.7	1.7	1.9	1.7	1.9	1.0	1.8	.93	1.2
	30	.78	1.1	.84	1.1	.86	.90	.83	.88	.80	.84	.76	.81
	5	1.9	2.0	2.3	2.5	2.5	2.7	2.5	2.7	2.6	2.8	2.7	2.9
	10	1.6	1.7	2.0	2.1	2.1	2.3	2.2	2.4	2.3	2.5	2.3	2.6
8	15	1.5	1.5	1.8	1.9	2.0	2.1	2.1	2.2	2.1	2.3	1.8	2.4
	20	1.4	1.5	1.7	1.8	1.9	2.0	1.8	2.1	1.4	2.1	1.0	1.6
	30	.79	1.1	.90	1.2	.93	.97	.91	.96	.87	.93	.84	.89
	5	1.9	2.1	2.5	2.7	2.7	2.9	2.8	3.0	2.9	3.1	3.0	3.3
	10	1.6	1.8	2.1	2.3	2.3	2.5	2.5	2.6	2.6	2.8	2.6	2.9
15	15	1.5	1.6	1.9	2.1	2.1	2.3	2.3	2.4	2.3	2.6	2.2	2.7
	20	1.4	1.5	1.8	2.0	2.0	2.2	2.1	2.3	1.8	2.4	1.2	2.1
	30	.75	1.1	.95	1.2	1.0	1.1	1.0	1.1	.99	1.0	.96	1.0
	5	1.7	1.9	2.5	2.7	2.8	3.0	3.0	3.2	3.2	3.4	3.3	3.6
	10	1.5	1.6	2.1	2.3	2.4	2.6	2.6	2.8	2.8	3.0	2.9	3.2
25	15	1.4	1.5	2.0	2.1	2.3	2.4	2.4	2.6	2.6	2.8	2.5	3.0
	20	1.3	1.4	1.9	2.0	2.1	2.3	2.2	2.5	2.1	2.6	1.3	2.5
	30	.67	.87	.93	.98	1.0	1.1	1.1	1.1	1.1	1.1	1.0	1.1

Table 6.--Predicted rate of spread in palmetto-gallberry fuel type where overstory density is 30 ft^2/acre (low) and palmetto coverage is 85 percent (continuous)

Age of rough (years)	Dead-fuel moisture	Height of understory (feet)											
		1		2		3		4		5		6	
		Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter
	Percent	Feet/minute											
1	5	.96	1.1	1.4	1.6	1.5	1.7	1.4	1.7	1.3	1.6	.92	1.5
	10	.80	.92	1.2	1.4	1.3	1.5	1.2	1.5	.83	1.4	.43	1.1
	15	.72	.81	1.1	1.2	1.1	1.4	.80	1.3	.44	.91	.39	.45
	20	.66	.75	.94	1.1	.75	1.2	.49	.75	.42	.49	.37	.43
	30	.30	.33	.42	.47	.43	.49	.38	.43	.33	.38	.29	.34
2	5	1.1	1.3	1.7	1.9	1.8	2.1	1.7	2.0	1.7	2.0	1.5	1.9
	10	.92	1.1	1.4	1.6	1.5	1.8	1.5	1.8	1.4	1.7	1.1	1.6
	15	.82	.92	1.2	1.4	1.4	1.6	1.3	1.6	.97	1.5	.52	1.2
	20	.75	.84	1.1	1.3	1.2	1.5	.88	1.4	.56	.93	.49	.57
	30	.36	.56	.52	.58	.55	.62	.50	.56	.44	.50	.39	.45
3	5	1.2	1.4	1.8	2.0	1.9	2.2	1.9	2.2	1.8	2.1	1.7	2.1
	10	.96	1.1	1.5	1.7	1.6	1.9	1.6	1.9	1.5	1.8	1.3	1.8
	15	.85	.96	1.3	1.5	1.5	1.7	1.4	1.7	1.2	1.6	.58	1.4
	20	.78	.87	1. 2	1.3	1.3	1.5	1.1	1.5	.62	1.2	.55	.63
	30	.39	.61	.56	.71	.59	.66	.55	.62	.49	.56	.43	.50
4	5	1.2	1.4	1.8	2.1	2.0	2.3	1.9	2.3	1.9	2.2	1.8	2.1
	10	.98	1.1	1.5	1.7	1.7	1.9	1.7	1.9	1.6	1.9	1.4	1.9
	15	.86	.97	1.3	1.5	1.5	1.7	1.5	1.7	1.3	1.7	.80	1.6
	20	.79	.88	1.2	1.4	1.4	1.6	1.2	1.6	.66	1.4	.58	.67
	30	.42	.63	.57	.79	.62	.69	.58	.65	.52	.59	.46	.53
5	5	1.2	1.4	1.8	2.1	2.0	2.4	2.0	2.3	1.9	2.3	1.8	2.2
	10	.98	1.1	1.5	1.7	1.7	2.0	1.7	2.0	1.7	2.0	1.5	1.9
	15	.86	.97	1.3	1.5	1.5	1.7	1.5	1.8	1.4	1.8	.96	1.7
	20	.79	.88	1.2	1.4	1.4	1.6	1.3	1.6	.72	1.5	.61	.85
	30	.43	.63	.58	.82	.63	.70	.59	.67	.54	.61	.48	.55
8	5	1.2	1.4	1.9	2.2	2.1	2.4	2.1	2.4	2.1	2.4	2.0	2.4
	10	.98	1.1	1.5	1.8	1.7	2.0	1.8	2.1	1.8	2.1	1.7	2.1
	15	.86	.97	1.4	1.5	1.6	1.8	1.6	1.9	1.5	1.9	1.2	1.8
	20	.79	.88	1.3	1.4	1.4	1.6	1.4	1.7	.99	1.6	.67	1.2
	30	.41	.63	.59	.84	.65	.72	.63	.70	.58	.66	.52	.60
15	5	1.1	1.2	1.7	2.0	2.0	2.3	2.1	2.5	2.1	2.5	2.1	2.5
	10	.88	1.0	1.4	1.6	1.7	1.9	1.8	2.1	1.9	2.2	1.8	2.2
	15	.78	.88	1.3	1.4	1.5	1.7	1.6	1.9	1.6	2.0	1.5	2.0
	20	.72	.81	1.2	1.3	1.4	1.6	1.4	1.7	1.2	1.8	.73	1.5
	30	.34	.54	.54	.71	.63	.70	.64	.72	.61	.69	.57	.65
25	5	.83	.96	1.4	1.7	1.8	2.1	2.0	2.3	2.1	2.5	2.1	2.5
	10	.69	.79	1.2	1.4	1.5	1.8	1.7	2.0	1.8	2.1	1.9	2.2
	15	.61	.70	1.1	1.2	1.4	1.6	1.5	1.8	1.6	1.9	1.6	2.0
	20	.57	.64	.99	1.1	1.3	1.4	1.4	1.6	1.3	1.7	.76	1.6
	30	.26	.37	.45	.50	.55	.61	.59	.67	.60	.67	.58	.66

Table 7.--Predicted flame lengths in palmetto-gallberry fuel type where overstory density is 70 ft^2/acre (medium) and palmetto coverage is 15 percent (sparse)

Age of rough (years)	Dead-fuel moisture	Height of understory (feet)											
		1		2		3		4		5		6	
		Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter
	Percent	Feet											
1	5	1.6	1.6	1.7	1.8	1.6	1.8	1.6	1.8	1.7	1.8	1.7	1.9
	10	1.3	1.3	1.4	1.5	1.4	1.5	1.4	1.5	1.5	1.6	1.3	1.7
	15	1.1	1.2	1.2	1.3	1.3	1.4	1.3	1.4	1.2	1.5	.66	1.3
	20	1.0	1.1	1.2	1.2	1.2	1.3	1.2	1.3	.67	1.2	.63	.67
	30	.81	.83	.93	.97	.67	.94	.60	.63	.55	.58	.52	.55
2	5	1.8	1.9	2.0	2.1	2.0	2.1	1.9	2.1	2.0	2.1	2.1	2.2
	10	1.5	1.5	1.7	1.7	1.7	1.8	1.7	1.8	1.7	1.9	1.8	2.0
	15	1.3	1.3	1.5	1.5	1.5	1.6	1.5	1.6	1.6	1.7	1.3	1.8
	20	1.2	1.2	1.4	1.4	1.4	1.5	1.5	1.6	1.3	1.6	.79	1.2
	30	.93	.96	1.1	1.1	1.0	1.2	.75	.78	.69	.73	.64	.68
3	5	1.8	1.9	2.1	2.2	2.1	2.2	2.0	2.2	2.1	2.2	2.1	2.3
	10	1.5	1.5	1.7	1.8	1.7	1.9	1.8	1.9	1.8	2.0	1.9	2.1
	15	1.3	1.4	1.5	1.6	1.6	1.7	1.6	1.7	1.7	1.8	1.5	1.9
	20	1.2	1.3	1.4	1.5	1.5	1.6	1.5	1.6	1.4	1.7	.83	1.4
	30	.96	.99	1.1	1.2	1.1	1.3	.78	.82	.72	.76	.68	.72
4	5	1.8	1.9	2.1	2.2	2.1	2.2	2.1	2.2	2.1	2.3	2.2	2.4
	10	1.5	1.6	1.7	1.8	1.8	1.9	1.8	1.9	1.8	2.0	1.9	2.1
	15	1.3	1.4	1.5	1.6	1.6	1.7	1.6	1.8	1.7	1.9	1.5	1.9
	20	1.2	1.3	1.4	1.5	1.5	1.6	1.6	1.7	1.4	1.7	.84	1.4
	30	.97	1.0	1.2	1.2	1.0	1.3	.79	.83	.73	.78	.69	.73
5	5	1.8	1.9	2.1	2.2	2.1	2.2	2.1	2.2	2.1	2.3	2.2	2.4
	10	1.5	1.6	1.7	1.8	1.8	1.9	1.8	1.9	1.9	2.0	1.9	2.1
	15	1.3	1.4	1.5	1.6	1.6	1.7	1.7	1.8	1.7	1.9	1.5	1.9
	20	1.2	1.3	1.4	1.5	1.5	1.6	1.6	1.7	1.4	1.7	.85	1.4
	30	.97	1.0	1.2	1.2	.97	1.3	.79	.83	.74	.78	.70	.74
8	5	1.8	1.9	2.1	2.2	2.1	2.2	2.1	2.3	2.2	2.3	2.2	2.5
	10	1.5	1.6	1.7	1.8	1.8	1.9	1.8	2.0	1.9	2.1	1.9	2.2
	15	1.3	1.4	1.6	1.7	1.6	1.7	1.7	1.8	1.7	1.9	1.4	2.0
	20	1.2	1.3	1.5	1.5	1.5	1.6	1.6	1.7	1.3	1.7	.86	1.3
	30	.98	1.0	1.1	1.2	.83	1.1	.79	.83	.74	.78	.70	.75
15	5	1.6	1.7	1.9	2.1	2.0	2.2	2.1	2.3	2.2	2.4	2.3	2.5
	10	1.4	1.4	1.6	1.8	1.8	1.9	1.9	2.0	2.0	2.1	1.9	2.3
	15	1.2	1.3	1.5	1.6	1.6	1.7	1.7	1.9	1.7	2.0	1.3	2.0
	20	1.2	1.2	1.4	1.5	1.5	1.7	1.5	1.8	.96	1.7	.85	1.1
	30	.81	.97	.76	1.1	.77	.81	.75	.79	.72	.77	.70	.74
25	5	1.3	1.5	1.8	1.9	2.0	2.1	2.1	2.3	2.3	2.4	2.3	2.6
	10	1.2	1.3	1.5	1.7	1.7	1.9	1.9	2.0	2.0	2.2	1.9	2.3
	15	1.1	1.2	1.4	1.5	1.6	1.7	1.7	1.9	1.6	2.0	1.1	2.0
	20	1.0	1.1	1.4	1.5	1.5	1.7	1.3	1.7	.84	1.6	.82	.88
	30	.51	.53	.65	.68	.69	.73	.70	.74	.69	.73	.67	.72

Table 8.--Predicted rate of spread in palmetto-gallberry fuel type where overstory density is 70 ft^2/acre (medium) and palmetto coverage is 15 percent (sparse)

Age of rough (years)	Dead-fuel moisture	Height of understory (feet)											
		1		2		3		4		5		6	
		Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter
	Percent	Feet/minute											
1	5	1.9	2.0	2.2	2.5	2.0	2.3	1.6	1.9	1.5	1.7	1.3	1.6
	10	1.4	1.5	1.8	1.9	1.6	1.8	1.4	1.6	1.3	1.5	.96	1.4
	15	1.2	1.2	1.5	1.6	1.4	1.6	1.3	1.4	1.0	1.3	.46	1.1
	20	1.0	1.1	1.3	1.5	1.3	1.5	1.1	1.3	.52	1.0	.43	.50
	30	.73	.76	.99	1.1	.65	.99	.51	.57	.41	.46	.34	.39
2	5	1.9	2.1	2.5	2.8	2.3	2.7	2.0	2.3	1.8	2.1	1.6	1.9
	10	1.5	1.6	1.9	2.1	1.9	2.1	1.7	1.9	1.5	1.8	1.4	1.7
	15	1.2	1.3	1.7	1.8	1.6	1.8	1.5	1.7	1.3	1.6	.98	1.5
	20	1.1	1.1	1.5	1.6	1.5	1.7	1.4	1.6	1.0	1.4	.55	.96
	30	.76	.80	1.1	1.2	.99	1.2	.63	.70	.52	.58	.43	.50
3	5	1.9	2.0	2.5	2.7	2.4	2.7	2.1	2.4	1.8	2.1	1.7	2.0
	10	1.4	1.5	1.9	2.1	1.9	2.2	1.7	2.0	1.6	1.8	1.4	1.8
	15	1.2	1.3	1.6	1.8	1.7	1.9	1.5	1.7	1.4	1.7	1.1	1.6
	20	1.1	1.1	1.5	1.6	1.5	1.7	1.4	1.6	1.1	1.5	.58	1.1
	30	.74	.79	1.1	1.2	1.0	1.2	.65	.72	.54	.61	.46	.52
4	5	1.8	1.9	2.4	2.7	2.3	2.7	2.0	2.4	1.8	2.2	1.7	2.0
	10	1.4	1.5	1.9	2.1	1.9	2.1	1.7	2.0	1.6	1.8	1.5	1.8
	15	1.1	1.2	1.6	1.8	1.6	1.8	1.5	1.7	1.4	1.7	1.1	1.6
	20	1.0	1.1	1.4	1.6	1.5	1.7	1.4	1.6	1.1	1.5	.59	1.1
	30	.72	.77	1.1	1.1	.95	1.2	.65	.72	.54	.61	.46	.53
5	5	1.7	1.8	2.3	2.6	2.3	2.6	2.0	2.4	1.8	2.2	1.7	2.0
	10	1.3	1.4	1.8	2.0	1.8	2.1	1.7	2.0	1.6	1.8	1.5	1.8
	15	1.1	1.2	1.6	1.7	1.6	1.8	1.5	1.7	1.4	1.7	1.1	1.6
	20	.98	1.1	1.4	1.5	1.5	1.6	1.4	1.6	1.1	1.5	.59	1.1
	30	.71	.75	1.0	1.1	.86	1.2	.64	.71	.54	.61	.46	.53
8	5	1.5	1.6	2.1	2.4	2.1	2.4	1.9	2.3	1.8	2.1	1.7	2.0
	10	1.2	1.3	1.7	1.9	1.7	2.0	1.6	1.9	1.6	1.8	1.4	1.8
	15	1.0	1.1	1.4	1.6	1.5	1.7	1.5	1.7	1.4	1.7	1.0	1.6
	20	.89	.98	1.3	1.5	1.4	1.6	1.3	1.6	.99	1.5	.58	1.0
	30	.66	.71	.95	1.1	.68	1.0	.60	.67	.52	.59	.46	.52
15	5	1.0	1.2	1.5	1.8	1.7	2.0	1.7	2.0	1.7	2.0	1.6	2.0
	10	.85	.96	1.3	1.4	1.4	1.6	1.5	1.7	1.4	1.7	1.3	1.7
	15	.74	.83	1.1	1.3	1.3	1.4	1.3	1.5	1.2	1.5	.84	1.5
	20	.67	.75	1.0	1.1	1.2	1.3	1.1	1.4	.65	1.3	.53	.74
	30	.43	.56	.49	.75	.53	.59	.51	.57	.46	.53	.42	.48
25	5	.65	.76	1.1	1.2	1.3	1.5	1.4	1.7	1.5	1.7	1.5	1.8
	10	.55	.63	.90	1.0	1.1	1.3	1.2	1.4	1.3	1.5	1.2	1.6
	15	.49	.56	.81	.93	1.0	1.2	1.1	1.3	1.0	1.4	.60	1.3
	20	.45	.51	.75	.86	.88	1.1	.78	1.2	.48	1.0	.46	.53
	30	.20	.23	.32	.36	.38	.42	.39	.44	.38	.43	.36	.42

Table 9.--Predicted flame lengths in palmetto-gallberry fuel type where overstory density is 70 ft^2/acre (medium) and palmetto coverage is 50 percent (broken)

Age of rough (years)	Dead-fuel moisture	Height of understory (feet)											
		1		2		3		4		5		6	
		Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter
	Percent	Feet											
1	5	1.5	1.6	1.7	1.8	1.7	1.9	1.7	1.9	1.8	2.0	1.8	2.1
	10	1.3	1.3	1.4	1.5	1.5	1.6	1.5	1.7	1.5	1.8	1.2	1.8
	15	1.1	1.2	1.3	1.4	1.4	1.5	1.4	1.5	1.1	1.6	.68	1.2
	20	1.1	1.1	1.2	1.3	1.3	1.4	1.0	1.4	.69	.95	.66	.70
	30	.83	.90	.68	.97	.66	.69	.61	.64	.57	.60	.54	.57
2	5	1.8	1.9	2.0	2.2	2.1	2.2	2.1	2.2	2.1	2.3	2.2	2.4
	10	1.5	1.6	1.7	1.8	1.8	1.9	1.8	2.0	1.9	2.0	1.8	2.2
	15	1.3	1.4	1.5	1.6	1.6	1.7	1.7	1.8	1.7	1.9	1.2	1.9
	20	1.2	1.3	1.5	1.5	1.5	1.6	1.5	1.7	1.1	1.7	.83	1.0
	30	.99	1.0	1.1	1.2	.82	1.0	.77	.81	.72	.76	.68	.72
3	5	1.8	1.9	2.1	2.3	2.2	2.4	2.2	2.4	2.2	2.4	2.3	2.5
	10	1.5	1.6	1.8	1.9	1.9	2.0	1.9	2.1	2.0	2.1	2.0	2.3
	15	1.4	1.4	1.6	1.7	1.7	1.8	1.8	1.9	1.8	2.0	1.5	2.0
	20	1.3	1.3	1.5	1.6	1.6	1.7	1.6	1.8	1.3	1.8	.89	1.3
	30	1.0	1.1	1.2	1.3	.86	1.1	.82	.86	.77	.81	.73	.77
4	5	1.8	2.0	2.2	2.3	2.2	2.4	2.2	2.4	2.3	2.5	2.4	2.6
	10	1.5	1.6	1.8	2.0	1.9	2.1	2.0	2.1	2.0	2.2	2.0	2.3
	15	1.4	1.5	1.7	1.8	1.7	1.9	1.8	1.9	1.8	2.0	1.6	2.1
	20	1.3	1.4	1.6	1.6	1.7	1.8	1.7	1.8	1.4	1.9	.91	1.4
	30	1.0	1.1	1.2	1.3	.88	1.1	.84	.88	.79	.83	.75	.79
5	5	1.8	2.0	2.2	2.3	2.3	2.4	2.3	2.5	2.3	2.5	2.4	2.6
	10	1.5	1.6	1.8	2.0	1.9	2.1	2.0	2.1	2.1	2.2	2.1	2.4
	15	1.4	1.5	1.7	1.8	1.8	1.9	1.8	2.0	1.9	2.1	1.6	2.1
	20	1.3	1.4	1.6	1.7	1.7	1.8	1.7	1.9	1.4	1.9	.93	1.5
	30	1.0	1.1	1.1	1.3	.89	1.1	.85	.89	.80	.85	.76	.81
8	5	1.8	2.0	2.2	2.4	2.3	2.5	2.4	2.5	2.4	2.6	2.5	2.7
	10	1.6	1.7	1.9	2.0	2.0	2.1	2.1	2.2	2.1	2.3	2.2	2.4
	15	1.4	1.5	1.7	1.8	1.8	1.9	1.9	2.0	1.9	2.1	1.7	2.2
	20	1.3	1.4	1.6	1.7	1.7	1.8	1.8	1.9	1.4	2.0	.96	1.6
	30	1.0	1.1	1.0	1.3	.89	.96	.86	.91	.82	.87	.79	.84
15	5	1.7	1.9	2.2	2.3	2.3	2.5	2.4	2.6	2.5	2.7	2.6	2.9
	10	1.5	1.6	1.9	2.0	2.0	2.2	2.1	2.3	2.2	2.4	2.3	2.6
	15	1.4	1.4	1.7	1.8	1.9	2.0	2.0	2.1	2.0	2.3	1.7	2.3
	20	1.3	1.4	1.6	1.7	1.8	1.9	1.8	2.0	1.3	2.0	1.0	1.6
	30	.69	1.0	.85	1.1	.88	.93	.87	.92	.85	.90	.82	.87
25	5	1.5	1.7	2.1	2.2	2.3	2.5	2.5	2.7	2.6	2.9	2.8	3.0
	10	1.3	1.4	1.8	1.9	2.0	2.2	2.2	2.4	2.3	2.6	2.4	2.7
	15	1.2	1.3	1.7	1.8	1.9	2.0	2.0	2.2	2.0	2.4	1.8	2.4
	20	1.2	1.2	1.6	1.7	1.8	1.9	1.7	2.1	1.2	2.1	1.0	1.6
	30	.58	.60	.77	.81	.83	.88	.85	.90	.84	.89	.83	.88

Table 10.--Predicted rate of spread in palmetto-gallberry fuel type where overstory density is 70 ft^2/acre (medium) and palmetto coverage is 50 percent (broken)

Age of rough (years)	Dead-fuel moisture	Height of understory (feet)											
		1		2		3		4		5		6	
		Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter
	Percent	Feet/minute											
1	5	1.3	1.5	1.8	2.1	1.8	2.1	1.6	1.9	1.5	1.8	1.3	1.7
	10	1.1	1.2	1.5	1.7	1.5	1.7	1.4	1.6	1.2	1.6	.82	1.4
	15	.92	1.0	1.3	1.5	1.4	1.5	1.2	1.5	.83	1.3	.46	.91
	20	.84	.92	1.2	1.3	1.2	1.4	.89	1.3	.51	.77	.44	.51
	30	.61	.69	.59	.91	.57	.64	.48	.54	.40	.46	.35	.40
2	5	1.5	1.7	2.1	2.4	2.2	2.5	2.0	2.3	1.8	2.1	1.7	2.0
	10	1.2	1.3	1.7	1.9	1.8	2.0	1.7	1.9	1.6	1.8	1.4	1.8
	15	1.0	1.1	1.5	1.7	1.6	1.8	1.5	1.7	1.3	1.7	.86	1.5
	20	.92	1.0	1.3	1.5	1.5	1.6	1.3	1.6	.81	1.4	.57	.75
	30	.68	.74	.92	1.1	.70	.91	.61	.68	.52	.59	.45	.51
3	5	1.5	1.7	2.1	2.4	2.2	2.6	2.1	2.4	1.9	2.2	1.8	2.1
	10	1.2	1.3	1.7	1.9	1.8	2.1	1.7	2.0	1.6	1.9	1.5	1.9
	15	1.0	1.1	1.5	1.7	1.6	1.8	1.6	1.8	1.4	1.7	1.1	1.6
	20	.92	1.0	1.4	1.5	1.5	1.7	1.4	1.7	1.0	1.5	.61	1.0
	30	.68	.74	.95	1.1	.72	1.0	.64	.71	.55	.62	.48	.55
4	5	1.5	1.6	2.1	2.4	2.2	2.6	2.1	2.4	1.9	2.3	1.8	2.2
	10	1.2	1.3	1.7	1.9	1.8	2.1	1.8	2.0	1.7	2.0	1.5	1.9
	15	1.0	1.1	1.5	1.7	1.6	1.8	1.6	1.8	1.5	1.8	1.1	1.7
	20	.90	.99	1.4	1.5	1.5	1.7	1.4	1.7	1.1	1.6	.63	1.1
	30	.67	.73	.93	1.1	.72	1.0	.65	.72	.56	.63	.49	.56
5	5	1.4	1.6	2.1	2.4	2.2	2.5	2.1	2.4	2.0	2.3	1.9	2.2
	10	1.1	1.3	1.7	1.9	1.8	2.1	1.8	2.0	1.7	2.0	1.6	1.9
	15	.98	1.1	1.5	1.7	1.6	1.8	1.6	1.8	1.5	1.8	1.2	1.7
	20	.88	.98	1.3	1.5	1.5	1.7	1.4	1.7	1.1	1.6	.63	1.1
	30	.66	.73	.90	1.1	.71	.96	.64	.72	.57	.64	.50	.57
8	5	1.3	1.5	2.0	2.3	2.1	2.4	2.1	2.4	2.0	2.3	1.9	2.2
	10	1.1	1.2	1.6	1.8	1.7	2.0	1.7	2.0	1.7	2.0	1.6	1.9
	15	.92	1.0	1.4	1.6	1.6	1.8	1.6	1.8	1.5	1.8	1.2	1.7
	20	.83	.93	1.3	1.4	1.4	1.6	1.4	1.7	1.1	1.6	.64	1.2
	30	.60	.69	.74	1.0	.67	.76	.63	.70	.56	.64	.50	.57
15	5	1.0	1.2	1.6	1.9	1.8	2.1	1.9	2.2	1.9	2.2	1.9	2.2
	10	.86	.98	1.3	1.5	1.5	1.8	1.6	1.9	1.6	1.9	1.6	1.9
	15	.75	.85	1.2	1.3	1.4	1.6	1.5	1.7	1.4	1.7	1.2	1.7
	20	.69	.78	1.1	1.2	1.3	1.5	1.3	1.6	.91	1.5	.63	1.1
	30	.34	.54	.51	.71	.57	.64	.57	.64	.53	.60	.49	.56
25	5	.73	.85	1.2	1.4	1.5	1.8	1.7	1.9	1.7	2.0	1.8	2.1
	10	.61	.70	1.0	1.2	1.3	1.5	1.4	1.7	1.5	1.8	1.5	1.8
	15	.54	.62	.92	1.1	1.2	1.3	1.3	1.5	1.3	1.6	1.1	1.6
	20	.50	.57	.85	.98	1.0	1.2	1.0	1.4	.69	1.4	.57	1.0
	30	.23	.25	.37	.42	.45	.50	.47	.53	.47	.53	.45	.51

Table 11.--Predicted flame lengths in palmetto-gallberry fuel type where overstory density is 70 ft^2/acre (medium) and palmetto coverage is 85 percent (continuous)

Age of rough (years)	Dead-fuel moisture	Height of understory (feet)											
		1		2		3		4		5		6	
		Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter
	Percent	Feet											
1	5	1.6	1.7	1.9	2.0	1.9	2.1	2.0	2.1	2.0	2.2	2.0	2.3
	10	1.3	1.4	1.6	1.7	1.7	1.8	1.7	1.9	1.7	2.0	1.4	2.0
	15	1.2	1.3	1.5	1.6	1.6	1.7	1.6	1.8	1.2	1.8	.77	1.4
	20	1.2	1.2	1.4	1.5	1.4	1.6	1.1	1.6	.78	1.1	.74	.79
	30	.63	.90	.72	.75	.71	.75	.68	.72	.64	.68	.61	.65
2	5	1.9	2.0	2.2	2.4	2.3	2.5	2.4	2.6	2.4	2.6	2.5	2.7
	10	1.6	1.7	1.9	2.0	2.0	2.2	2.1	2.2	2.2	2.3	2.1	2.4
	15	1.4	1.5	1.7	1.8	1.9	2.0	1.9	2.1	1.9	2.2	1.6	2.2
	20	1.3	1.4	1.6	1.7	1.8	1.9	1.8	2.0	1.3	1.9	.96	1.4
	30	1.0	1.1	.91	1.3	.90	.95	.87	.91	.82	.87	.78	.83
3	5	2.0	2.1	2.4	2.6	2.5	2.7	2.5	2.8	2.6	2.8	2.7	2.9
	10	1.7	1.8	2.0	2.2	2.2	2.3	2.2	2.4	2.3	2.5	2.3	2.6
	15	1.5	1.6	1.8	2.0	2.0	2.1	2.1	2.2	2.1	2.3	1.9	2.4
	20	1.4	1.5	1.7	1.8	1.9	2.0	1.9	2.1	1.7	2.1	1.0	1.8
	30	1.1	1.2	1.1	1.4	.98	1.1	.94	.99	.90	.95	.86	.91
4	5	2.0	2.2	2.5	2.7	2.6	2.8	2.7	2.9	2.7	2.9	2.8	3.0
	10	1.7	1.8	2.1	2.3	2.2	2.4	2.3	2.5	2.4	2.6	2.4	2.7
	15	1.5	1.6	1.9	2.0	2.1	2.2	2.1	2.3	2.2	2.4	2.1	2.5
	20	1.4	1.5	1.8	1.9	2.0	2.1	2.0	2.2	1.8	2.2	1.1	2.0
	30	1.1	1.2	1.2	1.5	1.0	1.3	.99	1.0	.94	1.0	.90	.96
5	5	2.1	2.2	2.5	2.7	2.7	2.9	2.7	2.9	2.8	3.0	2.9	3.1
	10	1.7	1.9	2.2	2.3	2.3	2.5	2.4	2.6	2.5	2.6	2.5	2.8
	15	1.6	1.7	2.0	2.1	2.1	2.2	2.2	2.3	2.3	2.5	2.2	2.5
	20	1.5	1.6	1.8	2.0	2.0	2.1	2.1	2.2	1.9	2.3	1.1	2.1
	30	1.1	1.3	1.2	1.5	1.0	1.3	1.0	1.1	.98	1.0	.93	.99
8	5	2.1	2.3	2.7	2.9	2.8	3.1	2.9	3.1	3.0	3.2	3.0	3.3
	10	1.8	1.9	2.3	2.4	2.4	2.6	2.5	2.7	2.6	2.8	2.7	2.9
	15	1.6	1.7	2.1	2.2	2.2	2.4	2.3	2.5	2.4	2.6	2.4	2.7
	20	1.5	1.6	1.9	2.1	2.1	2.2	2.2	2.4	2.1	2.5	1.4	2.4
	30	1.2	1.3	1.3	1.6	1.1	1.4	1.1	1.1	1.1	1.1	1.0	1.1
15	5	2.1	2.3	2.8	3.0	3.0	3.3	3.1	3.4	3.2	3.5	3.3	3.6
	10	1.8	1.9	2.4	2.5	2.6	2.8	2.7	2.9	2.9	3.1	3.0	3.2
	15	1.6	1.7	2.1	2.3	2.4	2.5	2.5	2.7	2.6	2.8	2.7	3.0
	20	1.5	1.6	2.0	2.1	2.3	2.4	2.4	2.6	2.3	2.7	1.9	2.7
	30	1.1	1.3	1.1	1.6	1.2	1.4	1.2	1.2	1.2	1.2	1.1	1.2
25	5	1.9	2.0	2.7	2.9	3.1	3.3	3.3	3.6	3.5	3.7	3.6	3.9
	10	1.6	1.7	2.3	2.5	2.7	2.9	2.9	3.1	3.0	3.3	3.2	3.4
	15	1.5	1.6	2.1	2.3	2.5	2.6	2.7	2.9	2.8	3.0	2.9	3.2
	20	1.4	1.5	2.0	2.1	2.3	2.5	2.5	2.7	2.5	2.9	2.2	2.9
	30	.74	1.1	1.1	1.5	1.2	1.2	1.2	1.3	1.2	1.3	1.2	1.3

Table 12.--Predicted rate of spread in palmetto-gallberry fuel type where overstory density is 70 ft^2/acre (medium) and palmetto coverage is 85 percent (continuous)

Age of rough (years)	Dead-fuel moisture	Height of understory (feet)											
		1		2		3		4		5		6	
		Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter
	Percent	Feet/minute											
1	5	1.2	1.3	1.7	2.0	1.8	2.1	1.7	2.0	1.6	2.0	1.5	1.9
	10	.95	1.1	1.4	1.6	1.5	1.8	1.5	1.8	1.4	1.7	1.0	1.6
	15	.84	.95	1.3	1.4	1.4	1.6	1.3	1.6	.93	1.5	.51	1.1
	20	.77	.86	1.2	1.3	1.2	1.5	.85	1.4	.56	.86	.49	.56
	30	.38	.58	.54	.60	.56	.63	.50	.57	.44	.50	.38	.44
2	5	1.4	1.5	2.0	2.3	2.2	2.6	2.1	2.5	2.0	2.4	1.9	2.3
	10	1.1	1.2	1.7	1.9	1.8	2.1	1.8	2.1	1.7	2.0	1.6	2.0
	15	.95	1.1	1.4	1.6	1.6	1.9	1.6	1.9	1.5	1.8	1.1	1.7
	20	.86	.96	1.3	1.5	1.5	1.7	1.4	1.7	.98	1.6	.65	1.1
	30	.60	.72	.67	1.0	.70	.78	.65	.73	.58	.65	.51	.58
3	5	1.4	1.6	2.1	2.4	2.3	2.7	2.3	2.6	2.2	2.5	2.1	2.4
	10	1.1	1.3	1.7	2.0	1.9	2.2	1.9	2.2	1.9	2.2	1.8	2.1
	15	.98	1.1	1.5	1.7	1.7	2.0	1.7	2.0	1.7	2.0	1.4	1.9
	20	.89	.98	1.4	1.5	1.6	1.8	1.6	1.8	1.3	1.8	.71	1.4
	30	.64	.74	.81	1.1	.75	.93	.70	.78	.63	.71	.56	.64
4	5	1.4	1.6	2.2	2.5	2.4	2.8	2.3	2.7	2.2	2.6	2.1	2.5
	10	1.1	1.3	1.8	2.0	2.0	2.3	2.0	2.3	1.9	2.2	1.8	2.2
	15	.98	1.1	1.5	1.7	1.8	2.0	1.8	2.0	1.7	2.0	1.5	2.0
	20	.89	.99	1.4	1.6	1.6	1.8	1.6	1.9	1.4	1.8	.75	1.6
	30	.64	.74	.85	1.1	.77	1.0	.73	.81	.66	.74	.59	.67
5	5	1.4	1.6	2.2	2.5	2.4	2.8	2.4	2.8	2.3	2.7	2.2	2.6
	10	1.1	1.3	1.8	2.0	2.0	2.3	2.0	2.3	2.0	2.3	1.9	2.2
	15	.98	1.1	1.5	1.7	1.8	2.0	1.8	2.1	1.8	2.1	1.6	2.0
	20	.89	.99	1.4	1.6	1.6	1.8	1.7	1.9	1.4	1.9	.78	1.6
	30	.64	.74	.86	1.2	.77	1.1	.74	.83	.68	.76	.61	.69
8	5	1.4	1.6	2.2	2.5	2.4	2.8	2.5	2.9	2.4	2.8	2.3	2.7
	10	1.1	1.3	1.8	2.0	2.0	2.3	2.1	2.4	2.0	2.4	2.0	2.3
	15	.97	1.1	1.5	1.7	1.8	2.0	1.9	2.1	1.8	2.1	1.7	2.1
	20	88	.98	1.4	1.6	1.6	1.9	1.7	2.0	1.6	2.0	.98	1.8
	30	.62	.73	.84	1.2	.78	1.1	.77	.85	.71	.80	.65	.73
15	5	1.2	1.4	2.0	2.3	2.3	2.7	2.4	2.8	2.5	2.9	2.4	2.8
	10	.99	1.1	1.6	1.8	1.9	2.2	2.1	2.4	2.1	2.4	2.1	2.5
	15	.86	.97	1.4	1.6	1.7	1.9	1.8	2.1	1.9	2.2	1.8	2.2
	20	.79	.88	1.3	1.5	1.6	1.8	1.7	2.0	1.6	2.0	1.2	2.0
	30	.50	.65	.63	1.0	.74	.95	.76	.85	.73	.82	.69	.78
25	5	.93	1.1	1.6	1.9	2.0	2.4	2.2	2.6	2.4	2.8	2.4	2.8
	10	.76	.87	1.3	1.5	1.7	1.9	1.9	2.2	2.0	2.3	2.1	2.4
	15	.67	.76	1.2	1.3	1.5	1.7	1.7	2.0	1.8	2.1	1.8	2.2
	20	.62	.69	1.1	1.2	1.4	1.6	1.6	1.8	1.6	1.9	1.3	2.0
	30	.30	.48	.51	.78	.64	.71	.69	.77	.69	.78	.68	.76

Table 13.--Predicted flame lengths in palmetto-gallberry fuel type where overstory density is 110 ft^2/acre (high) and palmetto coverage is 15 percent (sparse)

Age of rough (years)	Dead-fuel moisture	Height of understory (feet)											
		1		2		3		4		5		6	
		Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter
	Percent	Feet											
1	5	1.9	1.9	2.1	2.2	2.0	2.2	2.0	2.1	2.0	2.1	2.1	2.2
	10	1.5	1.5	1.7	1.8	1.7	1.8	1.7	1.8	1.8	1.9	1.8	2.0
	15	1.3	1.4	1.5	1.6	1.5	1.6	1.6	1.7	1.6	1.8	1.4	1.8
	20	1.2	1.3	1.4	1.5	1.4	1.5	1.5	1.6	1.3	1.6	.80	1.3
	30	.95	.97	1.1	1.1	1.1	1.2	.77	.80	.70	.74	.65	.69
2	5	2.1	2.2	2.4	2.5	2.4	2.6	2.4	2.6	2.4	2.5	2.4	2.6
	10	1.7	1.8	2.0	2.1	2.0	2.2	2.0	2.2	2.1	2.2	2.1	2.3
	15	1.5	1.6	1.8	1.8	1.8	1.9	1.8	2.0	1.9	2.0	1.9	2.2
	20	1.4	1.4	1.6	1.7	1.7	1.8	1.7	1.8	1.8	1.9	1.3	1.9
	30	1.1	1.1	1.3	1.3	1.4	1.4	.95	1.3	.88	.92	.82	.86
3	5	2.2	2.2	2.5	2.6	2.5	2.7	2.5	2.7	2.5	2.7	2.5	2.7
	10	1.8	1.8	2.1	2.2	2.1	2.2	2.1	2.3	2.1	2.3	2.2	2.4
	15	1.6	1.6	1.8	1.9	1.9	2.0	1.9	2.0	2.0	2.1	2.0	2.2
	20	1.4	1.5	1.7	1.8	1.8	1.9	1.8	1.9	1.8	2.0	1.5	2.0
	30	1.1	1.1	1.3	1.4	1.4	1.5	.99	1.4	.92	.97	.86	.91
4	5	2.2	2.2	2.5	2.6	2.6	2.7	2.5	2.7	2.5	2.7	2.6	2.8
	10	1.8	1.8	2.1	2.2	2.1	2.3	2.1	2.3	2.2	2.3	2.3	2.4
	15	1.6	1.6	1.8	1.9	1.9	2.0	1.9	2.1	2.0	2.2	2.0	2.3
	20	1.4	1.5	1.7	1.8	1.8	1.9	1.8	2.0	1.9	2.0	1.5	2.1
	30	1.1	1.2	1.4	1.4	1.4	1.5	1.0	1.4	.93	.98	.87	.92
5	5	2.1	2.2	2.5	2.6	2.5	2.7	2.5	2.7	2.5	2.7	2.6	2.8
	10	1.8	1.8	2.1	2.2	2.1	2.3	2.1	2.3	2.2	2.4	2.3	2.5
	15	1.6	1.6	1.8	1.9	1.9	2.0	2.0	2.1	2.0	2.2	2.1	2.3
	20	1.4	1.5	1.7	1.8	1.8	1.9	1.9	2.0	1.9	2.1	1.5	2.1
	30	1.1	1.2	1.4	1.4	1.4	1.5	1.0	1.4	.93	.98	.88	.93
8	5	2.1	2.2	2.5	2.6	2.5	2.7	2.5	2.7	2.5	2.8	2.6	2.8
	10	1.7	1.8	2.1	2.2	2.1	2.3	2.2	2.3	2.2	2.4	2.3	2.5
	15	1.5	1.6	1.8	1.9	1.9	2.0	2.0	2.1	2.1	2.2	2.1	2.3
	20	1.4	1.5	1.7	1.8	1.8	1.9	1.9	2.0	1.9	2.1	1.4	2.1
	30	1.1	1.2	1.4	1.4	1.3	1.5	.99	1.1	.93	.98	.88	.93
15	5	1.9	2.0	2.3	2.5	2.4	2.6	2.5	2.7	2.6	2.8	2.7	2.9
	10	1.6	1.7	1.9	2.1	2.1	2.2	2.2	2.3	2.3	2.4	2.4	2.6
	15	1.4	1.5	1.7	1.9	1.9	2.0	2.0	2.1	2.1	2.3	2.0	2.4
	20	1.3	1.4	1.6	1.7	1.8	1.9	1.9	2.0	1.8	2.1	1.1	2.0
	30	1.1	1.1	1.2	1.4	.96	1.3	.94	.99	.90	.95	.87	.92
25	5	1.6	1.7	2.1	2.2	2.3	2.5	2.4	2.7	2.6	2.8	2.7	2.9
	10	1.3	1.4	1.8	1.9	2.0	2.2	2.2	2.3	2.3	2.5	2.4	2.6
	15	1.2	1.3	1.6	1.8	1.9	2.0	2.0	2.2	2.1	2.3	1.9	2.4
	20	1.2	1.2	1.6	1.7	1.8	1.9	1.8	2.0	1.5	2.1	1.0	1.9
	30	.61	.90	.79	1.0	.85	.90	.86	.91	.85	.90	.83	.88

Table 14.--Predicted rate of spread in palmetto-gallberry fuel type where overstory density is 110 ft^2/acre (high) and palmetto coverage is 15 percent (sparse)

Age of rough (years)	Dead-fuel moisture	Height of understory (feet)											
		1		2		3		4		5		6	
		Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter
	Percent	Feet/minute											
1	5	2.1	2.3	2.7	3.0	2.5	2.8	2.1	2.4	1.8	2.1	1.7	2.0
	10	1.6	1.7	2.1	2.3	2.0	2.2	1.7	2.0	1.6	1.8	1.4	1.7
	15	1.3	1.4	1.8	1.9	1.7	1.9	1.5	1.7	1.4	1.6	1.0	1.5
	20	1.2	1.2	1.6	1.7	1.6	1.7	1.4	1.6	1.1	1.5	.57	1.0
	30	.81	.85	1.1	1.2	1.1	1.3	.66	.74	.54	.60	.45	.51
2	5	2.2	2.4	3.0	3.3	2.9	3.3	2.5	2.9	2.2	2.6	2.0	2.4
	10	1.7	1.8	2.3	2.5	2.3	2.6	2.0	2.3	1.9	2.1	1.7	2.0
	15	1.4	1.5	1.9	2.1	2.0	2.2	1.8	2.0	1.7	1.9	1.5	1.8
	20	1.2	1.3	1.7	1.9	1.8	2.0	1.7	1.9	1.5	1.8	.98	1.6
	30	.85	.88	1.2	1.3	1.3	1.5	.82	1.2	.68	.76	.57	.65
3	5	2.2	2.3	3.0	3.3	2.9	3.3	2.6	3.0	2.3	2.7	2.1	2.4
	10	1.6	1.7	2.3	2.5	2.3	2.6	2.1	2.4	1.9	2.2	1.8	2.1
	15	1.4	1.4	1.9	2.1	2.0	2.2	1.9	2.1	1.7	2.0	1.6	1.9
	20	1.2	1.3	1.7	1.9	1.8	2.0	1.7	1.9	1.6	1.8	1.1	1.7
	30	.83	.87	1.2	1.3	1.3	1.5	.84	1.3	.71	.79	.60	.68
4	5	2.1	2.2	2.9	3.2	2.9	3.3	2.6	3.0	2.3	2.7	2.1	2.5
	10	1.6	1.7	2.2	2.4	2.3	2.6	2.1	2.4	1.9	2.2	1.8	2.1
	15	1.3	1.4	1.9	2.1	2.0	2.2	1.9	2.1	1.7	2.0	1.6	1.9
	20	1.2	1.2	1.7	1.8	1.8	2.0	1.7	1.9	1.6	1.8	1.1	1.7
	30	.81	.86	1.2	1.3	1.3	1.5	.84	1.3	.71	.79	.61	.68
5	5	2.0	2.1	2.8	3.1	2.8	3.2	2.5	2.9	2.3	2.7	2.1	2.5
	10	1.5	1.6	2.2	2.4	2.2	2.5	2.1	2.4	1.9	2.2	1.8	2.1
	15	1.3	1.4	1.8	2.0	1.9	2.2	1.8	2.1	1.7	2.0	1.6	1.9
	20	1.1	1.2	1.6	1.8	1.8	1.9	1.7	1.9	1.6	1.8	1.1	1.7
	30	.79	.84	1.2	1.3	1.3	1.4	.82	1.2	.70	.79	.60	.68
8	5	1.7	1.9	2.5	2.8	2.6	2.9	2.4	2.8	2.2	2.6	2.1	2.4
	10	1.4	1.5	2.0	2.2	2.1	2.4	2.0	2.3	1.9	2.2	1.8	2.1
	15	1.2	1.3	1.7	1.9	1.8	2.0	1.8	2.0	1.7	2.0	1.6	1.9
	20	1.0	1.1	1.5	1.7	1.6	1.8	1.6	1.8	1.5	1.8	.98	1.7
	30	.74	.79	1.1	1.2	1.1	1.4	.77	.92	.68	.76	.59	.67
15	5	1.3	1.4	1.9	2.1	2.1	2.4	2.1	2.4	2.0	2.4	2.0	2.3
	10	1.0	1.1	1.5	1.7	1.7	2.0	1.7	2.0	1.7	2.0	1.7	2.0
	15	.87	.97	1.3	1.5	1.5	1.7	1.6	1.8	1.6	1.8	1.4	1.8
	20	.78	.87	1.2	1.3	1.4	1.6	1.4	1.7	1.3	1.7	.69	1.5
	30	.58	.64	.81	.99	.67	.99	.65	.72	.60	.67	.54	.62
25	5	.79	.91	1.3	1.5	1.6	1.8	1.7	2.0	1.7	2.1	1.8	2.1
	10	.65	.74	1.1	1.2	1.3	1.5	1.4	1.7	1.5	1.8	1.5	1.8
	15	.57	.65	.95	1.1	1.2	1.4	1.3	1.5	1.3	1.6	1.2	1.6
	20	.53	.59	.88	1.0	1.1	1.3	1.2	1.4	.95	1.4	.59	1.2
	30	.25	.41	.41	.56	.48	.53	.50	.56	.49	.55	.46	.53

Table 15.--Predicted flame lengths in palmetto-gallberry fuel type where overstory density is 110 ft^2/acre (high) and palmetto coverage is 50 percent (broken)

Age of rough (years)	Dead-fuel moisture	Height of understory (feet)											
		1		2		3		4		5		6	
		Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter
	Percent	Feet											
1	5	1.8	1.9	2.0	2.2	2.1	2.2	2.1	2.2	2.1	2.3	2.2	2.4
	10	1.5	1.6	1.7	1.8	1.8	1.9	1.8	1.9	1.9	2.0	1.8	2.1
	15	1.3	1.4	1.5	1.6	1.6	1.7	1.7	1.8	1.6	1.9	1.1	1.8
	20	1.2	1.3	1.4	1.5	1.5	1.6	1.5	1.7	1.0	1.6	.82	.93
	30	.99	1.0	1.1	1.2	.82	1.0	.77	.81	.71	.76	.67	.72
2	5	2.1	2.2	2.4	2.6	2.5	2.7	2.5	2.7	2.5	2.7	2.6	2.8
	10	1.7	1.8	2.0	2.2	2.1	2.3	2.1	2.3	2.2	2.4	2.3	2.5
	15	1.5	1.6	1.8	1.9	1.9	2.0	2.0	2.1	2.0	2.2	1.9	2.3
	20	1.4	1.5	1.7	1.8	1.8	1.9	1.9	2.0	1.8	2.1	1.0	1.9
	30	1.1	1.2	1.4	1.4	1.2	1.5	.96	1.0	.90	.95	.85	.90
3	5	2.1	2.2	2.5	2.7	2.6	2.8	2.6	2.8	2.6	2.8	2.7	2.9
	10	1.8	1.9	2.1	2.2	2.2	2.4	2.2	2.4	2.3	2.5	2.4	2.6
	15	1.6	1.7	1.9	2.0	2.0	2.1	2.1	2.2	2.1	2.3	2.1	2.4
	20	1.5	1.5	1.8	1.9	1.9	2.0	2.0	2.1	1.9	2.2	1.3	2.1
	30	1.2	1.2	1.4	1.5	1.3	1.6	1.0	1.1	.96	1.0	.90	.96
4	5	2.1	2.3	2.6	2.7	2.7	2.9	2.7	2.9	2.7	2.9	2.7	3.0
	10	1.8	1.9	2.1	2.3	2.3	2.4	2.3	2.5	2.3	2.5	2.4	2.6
	15	1.6	1.7	1.9	2.0	2.0	2.2	2.1	2.2	2.2	2.3	2.2	2.4
	20	1.5	1.6	1.8	1.9	1.9	2.0	2.0	2.1	2.0	2.2	1.4	2.2
	30	1.2	1.2	1.4	1.5	1.3	1.6	1.0	1.1	.98	1.0	.92	.98
5	5	2.1	2.3	2.6	2.7	2.7	2.9	2.7	2.9	2.7	2.9	2.8	3.0
	10	1.8	1.9	2.2	2.3	2.3	2.4	2.3	2.5	2.4	2.6	2.5	2.7
	15	1.6	1.7	1.9	2.1	2.1	2.2	2.1	2.3	2.2	2.4	2.2	2.5
	20	1.5	1.6	1.8	1.9	1.9	2.1	2.0	2.1	2.0	2.2	1.5	2.2
	30	1.2	1.2	1.5	1.5	1.3	1.6	1.0	1.1	.99	1.0	.94	.99
8	5	2.1	2.3	2.6	2.8	2.7	2.9	2.7	3.0	2.8	3.0	2.9	3.1
	10	1.8	1.9	2.2	2.3	2.3	2.5	2.4	2.5	2.4	2.6	2.5	2.7
	15	1.6	1.7	2.0	2.1	2.1	2.2	2.2	2.3	2.3	2.4	2.3	2.6
	20	1.5	1.6	1.9	2.0	2.0	2.1	2.1	2.2	2.0	2.3	1.5	2.3
	30	1.2	1.3	1.4	1.6	1.1	1.6	1.1	1.1	1.0	1.1	.96	1.0
15	5	2.0	2.1	2.5	2.7	2.7	2.9	2.8	3.0	2.9	3.1	3.0	3.2
	10	1.7	1.8	2.1	2.3	2.3	2.5	2.4	2.6	2.5	2.7	2.6	2.9
	15	1.5	1.6	1.9	2.1	2.1	2.3	2.3	2.4	2.3	2.5	2.3	2.7
	20	1.4	1.5	1.8	1.9	2.0	2.1	2.1	2.3	2.0	2.4	1.4	2.3
	30	1.1	1.2	1.1	1.5	1.1	1.3	1.0	1.1	1.0	1.1	.98	1.0
25	5	1.7	1.8	2.3	2.5	2.6	2.9	2.8	3.0	2.9	3.2	3.1	3.3
	10	1.5	1.6	2.0	2.2	2.3	2.5	2.5	2.7	2.6	2.8	2.7	3.0
	15	1.3	1.4	1.9	2.0	2.1	2.3	2.3	2.5	2.4	2.6	2.4	2.8
	20	1.3	1.3	1.8	1.9	2.0	2.2	2.1	2.3	2.0	2.4	1.2	2.4
	30	.66	.97	.90	1.1	.98	1.0	1.0	1.1	1.0	1.1	.98	1.0

Table 16.--Predicted rate of spread in palmetto-gallberry fuel type where overstory density is 110 ft^2/acre (high) and palmetto coverage is 50 percent (broken)

Age of rough (years)	Dead-fuel moisture	Height of understory (feet)											
		1		2		3		4		5		6	
		Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter
	Percent	Feet/minute											
1	5	1.6	1.8	2.2	2.5	2.2	2.6	2.0	2.3	1.8	2.1	1.7	2.0
	10	1.3	1.4	1.8	2.0	1.8	2.1	1.7	1.9	1.6	1.8	1.4	1.8
	15	1.1	1.2	1.5	1.7	1.6	1.8	1.5	1.7	1.3	1.7	.82	1.5
	20	.96	1.1	1.4	1.5	1.5	1.7	1.4	1.6	.79	1.4	.57	.70
	30	.71	.77	.98	1.1	.72	.97	.62	.69	.52	.59	.45	.51
2	5	1.8	1.9	2.5	2.8	2.6	3.0	2.4	2.8	2.2	2.6	2.1	2.4
	10	1.4	1.5	2.0	2.2	2.1	2.4	2.0	2.3	1.9	2.2	1.8	2.1
	15	1.2	1.3	1.7	1.9	1.9	2.1	1.8	2.0	1.7	2.0	1.5	1.9
	20	1.0	1.1	1.6	1.7	1.7	1.9	1.7	1.9	1.5	1.8	.74	1.6
	30	.76	.82	1.2	1.3	1.0	1.4	.77	.86	.67	.75	.58	.65
3	5	1.8	1.9	2.6	2.9	2.7	3.1	2.5	2.9	2.3	2.7	2.2	2.5
	10	1.4	1.5	2.0	2.3	2.2	2.5	2.1	2.4	2.0	2.3	1.9	2.2
	15	1.2	1.3	1.7	1.9	1.9	2.2	1.9	2.1	1.8	2.0	1.6	2.0
	20	1.0	1.1	1.6	1.7	1.7	1.9	1.7	1.9	1.6	1.9	.97	1.7
	30	.76	.82	1.2	1.3	1.1	1.4	.81	.89	.71	.79	.61	.70
4	5	1.7	1.9	2.5	2.8	2.7	3.1	2.5	2.9	2.3	2.7	2.2	2.6
	10	1.3	1.5	2.0	2.3	2.2	2.5	2.1	2.4	2.0	2.3	1.9	2.2
	15	1.1	1.3	1.7	1.9	1.9	2.1	1.9	2.1	1.8	2.1	1.6	2.0
	20	1.0	1.1	1.6	1.7	1.7	1.9	1.7	2.0	1.6	1.9	1.0	1.7
	30	.75	.81	1.2	1.3	1.1	1.4	.81	.90	.72	.80	.63	.71
5	5	1.7	1.9	2.5	2.8	2.7	3.0	2.5	2.9	2.4	2.7	2.2	2.6
	10	1.3	1.5	2.0	2.2	2.2	2.5	2.1	2.4	2.0	2.3	1.9	2.2
	15	1.1	1.2	1.7	1.9	1.9	2.1	1.9	2.1	1.8	2.1	1.7	2.0
	20	1.0	1.1	1.5	1.7	1.7	1.9	1.7	2.0	1.6	1.9	1.1	1.8
	30	.74	.80	1.1	1.3	1.0	1.4	.81	.89	.72	.80	.63	.71
8	5	1.5	1.7	2.3	2.7	2.5	2.9	2.5	2.9	2.3	2.7	2.2	2.6
	10	1.2	1.4	1.9	2.1	2.1	2.3	2.1	2.4	2.0	2.3	1.9	2.3
	15	1.0	1.2	1.6	1.8	1.8	2.0	1.8	2.1	1.8	2.1	1.7	2.0
	20	.94	1.0	1.5	1.6	1.7	1.9	1.7	1.9	1.6	1.9	1.1	1.8
	30	.70	.77	1.1	1.2	.82	1.3	.78	.87	.71	.79	.63	.72
15	5	1.2	1.4	1.9	2.2	2.2	2.5	2.2	2.6	2.2	2.6	2.2	2.6
	10	.98	1.1	1.5	1.8	1.8	2.1	1.9	2.2	1.9	2.2	1.9	2.2
	15	.86	.96	1.4	1.5	1.6	1.8	1.7	1.9	1.7	2.0	1.6	2.0
	20	.78	.87	1.2	1.4	1.5	1.7	1.6	1.8	1.4	1.8	.92	1.7
	30	.54	.65	.70	1.0	.70	.94	.70	.78	.66	.74	.61	.69
25	5	.84	.97	1.4	1.6	1.7	2.0	1.9	2.2	2.0	2.3	2.0	2.4
	10	.69	.80	1.2	1.4	1.5	1.7	1.6	1.9	1.7	2.0	1.8	2.1
	15	.61	.70	1.0	1.2	1.3	1.5	1.5	1.7	1.5	1.8	1.5	1.9
	20	.57	.63	.97	1.1	1.2	1.4	1.3	1.6	1.2	1.7	.71	1.6
	30	.27	.42	.45	.61	.54	.60	.57	.64	.57	.64	.55	.62

Table 17.--Predicted flame lengths in palmetto-gallberry fuel type where overstory density is 110 ft^2/acre (high) and palmetto coverage is 85 percent (continuous)

Age of rough (years)	Dead-fuel moisture	Height of understory (feet)											
		1		2		3		4		5		6	
		Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter
	Percent	Feet											
1	5	1.8	1.9	2.2	2.3	2.3	2.4	2.3	2.5	2.3	2.5	2.4	2.6
	10	1.5	1.6	1.8	2.0	1.9	2.1	2.0	2.2	2.1	2.2	2.0	2.3
	15	1.4	1.5	1.7	1.8	1.8	1.9	1.8	2.0	1.8	2.1	1.3	2.0
	20	1.3	1.4	1.6	1.7	1.7	1.8	1.6	1.9	1.0	1.8	.91	1.1
	30	.97	1.1	.86	1.2	.87	.91	.83	.87	.78	.83	.74	.79
2	5	2.1	2.3	2.6	2.8	2.7	2.9	2.8	3.0	2.8	3.0	2.9	3.1
	10	1.8	1.9	2.2	2.3	2.3	2.5	2.4	2.6	2.4	2.6	2.5	2.7
	15	1.6	1.7	2.0	2.1	2.1	2.3	2.2	2.3	2.3	2.4	2.2	2.5
	20	1.5	1.6	1.9	2.0	2.0	2.1	2.1	2.2	2.0	2.3	1.3	2.2
	30	1.2	1.3	1.4	1.6	1.1	1.6	1.0	1.1	1.0	1.1	.95	1.0
3	5	2.2	2.4	2.8	2.9	2.9	3.1	2.9	3.2	3.0	3.2	3.0	3.3
	10	1.9	2.0	2.3	2.5	2.5	2.7	2.5	2.7	2.6	2.8	2.7	2.9
	15	1.7	1.8	2.1	2.2	2.3	2.4	2.3	2.5	2.4	2.6	2.4	2.7
	20	1.6	1.7	2.0	2.1	2.1	2.3	2.2	2.4	2.2	2.4	1.7	2.4
	30	1.3	1.3	1.5	1.7	1.2	1.7	1.1	1.2	1.1	1.1	1.0	1.1
4	5	2.3	2.4	2.8	3.0	3.0	3.2	3.0	3.3	3.1	3.3	3.1	3.4
	10	1.9	2.0	2.4	2.5	2.6	2.7	2.6	2.8	2.7	2.9	2.8	3.0
	15	1.7	1.8	2.2	2.3	2.3	2.5	2.4	2.6	2.5	2.7	2.5	2.8
	20	1.6	1.7	2.0	2.1	2.2	2.3	2.3	2.4	2.3	2.5	1.9	2.5
	30	1.3	1.4	1.6	1.7	1.3	1.8	1.2	1.2	1.1	1.2	1.1	1.1
5	5	2.3	2.4	2.9	3.1	3.1	3.3	3.1	3.4	3.1	3.4	3.2	3.5
	10	1.9	2.1	2.4	2.6	2.6	2.8	2.7	2.9	2.7	3.0	2.8	3.1
	15	1.7	1.8	2.2	2.3	2.4	2.5	2.5	2.6	2.5	2.7	2.6	2.8
	20	1.6	1.7	2.1	2.2	2.2	2.4	2.3	2.5	2.4	2.6	2.0	2.6
	30	1.3	1.4	1.6	1.8	1.3	1.8	1.2	1.3	1.2	1.2	1.1	1.2
8	5	2.3	2.5	3.0	3.2	3.2	3.4	3.3	3.5	3.3	3.6	3.4	3.7
	10	2.0	2.1	2.5	2.7	2.7	2.9	2.8	3.0	2.9	3.1	3.0	3.2
	15	1.8	1.9	2.3	2.4	2.5	2.6	2.6	2.8	2.7	2.9	2.7	3.0
	20	1.7	1.7	2.1	2.3	2.3	2.5	2.5	2.6	2.5	2.7	2.3	2.8
	30	1.3	1.4	1.7	1.8	1.4	1.9	1.3	1.4	1.2	1.3	1.2	1.2
15	5	2.3	2.5	3.1	3.3	3.3	3.6	3.5	3.8	3.6	3.9	3.7	4.0
	10	1.9	2.1	2.6	2.8	2.9	3.1	3.0	3.2	3.1	3.4	3.2	3.5
	15	1.7	1.9	2.3	2.5	2.6	2.8	2.8	3.0	2.9	3.1	3.0	3.2
	20	1.6	1.7	2.2	2.3	2.5	2.6	2.6	2.8	2.7	2.9	2.5	3.0
	30	1.3	1.4	1.6	1.9	1.3	1.9	1.3	1.4	1.3	1.4	1.3	1.4
25	5	2.0	2.2	3.0	3.2	3.4	3.6	3.6	3.9	3.8	4.1	3.9	4.2
	10	1.7	1.8	2.5	2.7	2.9	3.1	3.1	3.4	3.3	3.5	3.4	3.7
	15	1.6	1.7	2.3	2.5	2.7	2.8	2.9	3.1	3.1	3.3	3.2	3.4
	20	1.5	1.6	2.2	2.3	2.5	2.7	2.7	2.9	2.8	3.1	2.7	3.2
	30	1.0	1.2	1.2	1.8	1.3	1.8	1.4	1.4	1.4	1.4	1.4	1.4

Table 18.--Predicted rate of spread in palmetto-gallberry fuel type where overstory density is 110 ft^2/acre (high) and palmetto coverage is 85 percent (continuous)

Age of rough (years)	Dead-fuel moisture	Height of understory (feet)											
		1		2		3		4		5		6	
		Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter
	Percent	Feet/minute											
1	5	1.4	1.5	2.0	2.3	2.2	2.5	2.1	2.4	1.9	2.3	1.8	2.2
	10	1.1	1.2	1.6	1.9	1.8	2.1	1.8	2.0	1.7	2.0	1.5	1.9
	15	.95	1.1	1.4	1.6	1.6	1.8	1.6	1.8	1.4	1.8	.92	1.6
	20	.87	.96	1.3	1.5	1.5	1.7	1.4	1.7	.76	1.5	.61	.79
	30	.59	.72	.65	1.0	.69	.76	.63	.70	.55	.62	.48	.55
2	5	1.6	1.8	2.4	2.7	2.6	3.0	2.5	2.9	2.4	2.8	2.3	2.6
	10	1.2	1.4	1.9	2.2	2.1	2.4	2.1	2.4	2.0	2.3	1.9	2.3
	15	1.1	1.2	1.7	1.9	1.9	2.1	1.9	2.2	1.8	2.1	1.6	2.1
	20	.97	1.1	1.5	1.7	1.7	1.9	1.7	2.0	1.6	1.9	.90	1.7
	30	.72	.79	1.1	1.2	.85	1.3	.80	.88	.71	.80	.63	.72
3	5	1.6	1.8	2.5	2.8	2.7	3.2	2.7	3.1	2.5	3.0	2.4	2.8
	10	1.3	1.4	2.0	2.2	2.2	2.6	2.2	2.6	2.2	2.5	2.1	2.4
	15	1.1	1.2	1.7	1.9	2.0	2.2	2.0	2.3	1.9	2.2	1.8	2.2
	20	.99	1.1	1.6	1.7	1.8	2.0	1.8	2.1	1.7	2.1	1.2	1.9
	30	.74	.80	1.1	1.3	.93	1.4	.85	.94	.77	.86	.69	.78
4	5	1.6	1.8	2.5	2.8	2.8	3.2	2.7	3.2	2.6	3.0	2.5	2.9
	10	1.3	1.4	2.0	2.3	2.3	2.6	2.3	2.6	2.2	2.6	2.1	2.5
	15	1.1	1.2	1.7	1.9	2.0	2.3	2.0	2.3	2.0	2.3	1.9	2.3
	20	.99	1.1	1.6	1.7	1.8	2.0	1.9	2.1	1.8	2.1	1.4	2.0
	30	.74	.80	1.1	1.3	.99	1.5	.87	.97	.80	.89	.72	.81
5	5	1.6	1.8	2.5	2.8	2.8	3.2	2.8	3.2	2.7	3.1	2.5	3.0
	10	1.3	1.4	2.0	2.3	2.3	2.6	2.3	2.7	2.3	2.6	2.2	2.5
	15	1.1	1.2	1.7	1.9	2.0	2.3	2.1	2.3	2.0	2.3	1.9	2.3
	20	.98	1.1	1.6	1.7	1.8	2.1	1.9	2.1	1.8	2.2	1.5	2.1
	30	.73	.80	1.1	1.3	1.0	1.5	.89	.98	.82	.91	.74	.83
8	5	1.5	1.7	2.5	2.8	2.8	3.2	2.8	3.3	2.7	3.2	2.6	3.1
	10	1.2	1.4	2.0	2.2	2.3	2.6	2.3	2.7	2.3	2.7	2.3	2.6
	15	1.1	1.2	1.7	1.9	2.0	2.3	2.1	2.4	2.1	2.4	2.0	2.4
	20	.96	1.1	1.6	1.7	1.8	2.1	1.9	2.2	1.9	2.2	1.6	2.2
	30	.71	.79	1.1	1.3	.97	1.5	.90	1.0	.85	.95	.77	.87
15	5	1.3	1.5	2.2	2.5	2.6	3.0	2.8	3.2	2.8	3.2	2.7	3.2
	10	1.1	1.2	1.8	2.0	2.1	2.5	2.3	2.6	2.3	2.7	2.3	2.7
	15	.94	1.1	1.6	1.8	1.9	2.1	2.0	2.3	2.1	2.4	2.1	2.5
	20	.85	.95	1.4	1.6	1.7	1.9	1.9	2.1	1.9	2.2	1.7	2.2
	30	.61	.71	.93	1.2	.84	1.3	.88	.97	.85	.95	.80	.90
25	5	1.0	1.2	1.8	2.1	2.3	2.6	2.5	2.9	2.6	3.1	2.7	3.1
	10	.83	.95	1.5	1.7	1.9	2.1	2.1	2.4	2.2	2.6	2.3	2.6
	15	.73	.82	1.3	1.5	1.7	1.9	1.9	2.1	2.0	2.3	2.1	2.4
	20	.66	.74	1.2	1.3	1.5	1.7	1.7	2.0	1.8	2.1	1.7	2.2
	30	.42	.55	.62	.95	.72	1.1	.78	.87	.79	.89	.77	.87

Table 19.--Wind-effect category for low overstory stand density (basal area = 30 ft^2/acre)

Age of rough (year)	Visual height of understory (feet)					
	1	2	3	4	5	6
	Palmetto coverage sparse (15 percent)					
1	B	A	A	A		
2	C	A	A	A	A	
3	C	A	A	A	A	B
5	C	B	A	A	B	B
8		B	B	B	B	B
15			B	B	B	B
25			C	C	C	C
	Palmetto coverage broken (50 percent)					
1	C	A	A	A		
2	C	B	A	A	B	
3	C	B	B	B	B	B
5	C	B	B	B	B	B
8		C	B	B	B	B
15			C	B	B	B
25			C	C	C	C
	Palmetto coverage continuous (85 percent)					
1	C	B	B	B		
2	D	B	B	B	B	
3	D	C	B	B	B	B
5	D	C	B	B	B	B
8		C	C	B	B	B
15			C	C	C	C
25			D	C	C	C

Table 20.--Wind-effect category for medium overstory stand density (basal area = 70 ft^2/acre)

Age of rough (year)	Visual height of understory (feet)					
	1	2	3	4	5	6
	Palmetto coverage sparse (15 percent)					
1	C	A	A	A		
2	C	B	A	A	B	
3	C	B	B	A	B	B
5	C	B	B	B	B	B
8		B	B	B	B	B
15			C	B	B	B
25			C	C	C	C
	Palmetto coverage broken (50 percent)					
1	C	B	A	A		
2	C	B	B	B	B	
3	D	B	B	B	B	B
5	D	C	B	B	B	B
8		C	B	B	B	B
15			C	C	C	C
25			D	C	C	C
	Palmetto coverage continuous (85 percent)					
1	C	B	B	B		
2	D	C	B	B	B	
3	D	C	B	B	B	B
5	D	C	C	B	B	B
8		C	C	C	B	B
15			C	C	C	C
25			D	D	C	C

Table 21.--Wind-effect category for high overstory stand density (basal area = 110 ft^2/acre)

Age of rough (year)	Visual height of understory (feet)					
	1	2	3	4	5	6
	Palmetto coverage sparse (15 percent)					
1	C	B	A	A		
2	C	B	B	B	B	
3	D	B	B	B	B	B
5	D	C	B	B	B	B
8		C	B	B	B	B
15			C	B	B	B
25			C	C	C	C
	Palmetto coverage broken (50 percent)					
1	C	B	B	A		
2	D	C	B	B	B	
3	D	C	B	B	B	B
5	D	C	B	B	B	B
8		C	C	B	B	B
15			C	C	C	C
25			D	C	C	C
	Palmetto coverage continuous (85 percent)					
1	D	C	B	B		
2	D	C	B	B	B	
3	D	C	C	B	B	B
5	D	C	C	B	B	B
8		D	C	C	C	C
15			C	C	C	C
25			D	D	C	C

PART II: RESEARCH DOCUMENTATION

APPROACH AND PROCEDURES

Rothermel's (1972) rate-of-spread model [with minor revisions (Albini 1976a)] and several other mathematical models of fire behavior and effects are stored permanently at the Lawrence Berkeley Laboratories computer center, University of California, Berkeley. Variables needed for input to the rate-of-spread model include:

1. Loadings by size class of live- and dead-fuel components (dry weight, lb/ft^2)
2. Moisture contents of these components (fraction of dry weight)
3. Surface area/volume ratios (ft^{-1})
4. Heat of combustion (Btu/lb)
5. Mass density (lb/ft^3)
6. Ash fraction (fraction of dry weight)
7. Silica-free ash content (fraction of dry weight)
8. Depth of the fuel bed (ft)
9. Midflame windspeed (ft/min)
10. Slope of the terrain (ft vertical rise/ft horizontal)
11. Moisture content of extinction (fraction of dry weight).

Fuel data were collected for individual species or major groups of similar species (such as miscellaneous shrubs) for use with the Rothermel fire-spread model. Since the model does not accept negative windspeeds (backfires), a windspeed of zero was assumed for backfires. Model predictions were then compared with backfire rates of spread and flame lengths, and adjustments were made in input characteristics until close agreement was reached between predicted and observed spread rates and flame lengths. Once comparable predicted and observed values were obtained, the fuel data were summarized into general categories and size classes so that values for each individual species would not have to be used. These "standard" values were reentered in the spread model to see if predicted and actual rates of spread and flame length still agreed closely.

Fuel Sampling

Limited data for the palmetto-gallberry fuel complex were first entered in the rate-of-spread model in 1970.[7] Values for various species were developed from samples of material collected on plots having different ages of rough (Sackett 1975). In this trial, the Rothermel spread model grossly underestimated rate of spread. Since then, data from many more sample plots have been

[7] Data on file at the Southern Forest Fire Laboratory, Macon, Ga.

collected, and the needed fuel characteristics have been measured more precisely under a wide variety of palmetto-gallberry fuel conditions. Field sampling procedures and general characteristics of the sampled stands were described, and equations to predict the loading by size class for each main fuel category were developed by McNab and others.[8]

Ratios of surface area to volume (S/V) were determined on photomicrographs of cross sections of material that could not be idealized as a flat plate or cylinder. In these cases, a factor was established relating particle size (inches) to S/V (in^2/in^3) as measured on the photomicrographs. For particles with approximate idealized shapes, a factor was assumed (table 22). Then only diameter or thickness was measured at the midpoint of a sample of particles, averaged, and S/V (ft^2/ft^3) calculated as follows:

$$S/V = \frac{F \times 12}{t}$$ where F = shape factor and t = particle size in inches.

Table 22.--Factors used in calculating S/V ratio (ft^{-1}) from measurements of particle thickness or diameter (in), where $S/V = \frac{\text{factor} \times 12}{\text{thickness or diameter}}$

Species, condition, and size class	Factor	Standard deviation
Nonidealized shapes:		
Live slash pine needles (crowns)	3.607	± 0.26
Dead slash pine needles (litter)	4.064	± 0.49
Live and dead palmetto stems 0-¼"	3.758	± 0.20
Live and dead palmetto stems ¼-1"	3.918	± 0.18
Live and dead wiregrass foliage	3.620	± 0.57
Idealized flat plates:		
Live and dead palmetto foliage	2.0	
Live and dead gallberry foliage	2.0	
Live and dead misc. shrub foliage	2.0	
Live and dead herbaceous foliage (forbs and wide-bladed grasses)	2.0	
Idealized cylinders:		
Live and dead gallberry stems	4.0	
Live and dead herbaceous stems (flower stalks)	4.0	
Live and dead misc. shrub stems	4.0	

Particle density was determined by weighing a fuel sample submerged in a tank of water and dividing the sample dry weight by the submerged weight. Total mineral content[9] was obtained in a muffle furnace (Hough 1969). Silica content[9] was determined by acid digestion of the other inorganics, and "effective" mineral content was calculated by subtracting silica content from total mineral content. Heat value[9] was determined in an oxygen bomb calorimeter (Hough 1969).

[8] McNab, W. H., M. B. Edwards, Jr., and W. A. Hough. Estimating weight of fuel components in slash pine/saw-palmetto/gallberry stands. (In preparation for For. Sci.)

[9] Total mineral, silica, and heat content for many fuel samples were measured through work contracted to the Engineering Experiment Station, Georgia Institute of Technology, Atlanta, Ga.

Eleven of the plots having completely documented samples of fuel were burned with prescription backfires. The length of active fireline varied from 650 to 2,500 feet, and the fires burned for 30 to 60 minutes. On plots where burns were observed, windspeeds in the stand were measured during the fire, and moisture contents of the different fuel size classes and types were measured immediately before the fire. Rate of fire spread, flame length, fuel consumption, and smoke production were also estimated as precisely as possible on these burns.

Data Handling

The first step in developing the dynamic fuel model was to establish proper values for the fuel-bed descriptors, which were poorly defined by contemporary measurement techniques. Descriptors included (1) moisture of extinction, (2) fuel-bed depth, and (3) amount of litter layer to include in the fuel model. To establish these parameters, Rothermel's rate-of-spread model was repeatedly applied on the most complete data available--11 test fire plots on which fuel characteristics, spread rate, and flame-length measurements were well documented. The ill-defined quantities were varied systematically over a representative range, and values for these quantities were selected which gave the most faithful predictions of experimental fire behavior. The computations were carried out from the remote-user facility at the Northern Forest Fire Laboratory in Missoula, Montana.

Moisture of extinction.--With this variable, we were guided by laboratory tests (Blackmarr 1972) and by the many years of prescribed burning experience of our staff at the Southern Forest Fire Laboratory. Blackmarr's ignition tests, as well as full-scale test burns, indicated that fire would spread poorly, if at all, in Southern pine needle litter when moisture content of the needles exceeded 45 percent. In a series of test fires in needle litter fuel beds, the model best predicted rate of spread when extinction moisture was entered at 40 percent. If values greater than 40 percent were entered, the predicted spread rate in low-moisture fuels was greater than the observed value; if a lesser value of moisture of extinction was used, the predicted rate of spread was generally less than the observed. This exercise in "variable tuning" emphasized a deficiency in current modeling capability--namely, that the specification of such a sensitive parameter should not remain an "input variable" because there are no simple ways for field personnel to measure or sample this variable. It should be determined by other physical descriptors of the fuel complex. Research is currently in progress at the Northern Forest Fire Laboratory to establish the relevant relationships.

Death of the fuel bed.--This descriptor is deceptively simple for a mixed fuel complex. For nearly uniform natural fuel beds, such as grass fields or continuous brush stands, the depth of the modeled fuel bed is the height of the standing vegetation. Palmetto-gallberry and other mixed fuel associations vary considerably in height on any specific site. The proper value to enter for such beds is the depth of an equivalent fuel bed, loaded with the same average quantities of fuel elements, which would burn with the same rate of spread and intensity as the average for the irregular fuel bed. The relation between this depth and observed average depth of the mixed fuel complex being burned is not necessarily obvious. By a series of systematic trials, it was determined that

a value of two-thirds of the visual understory fuel-bed depth gave the most consistent agreement between observed and predicted rate of spread values and flame lengths. In these trials, the moisture of extinction was held at 40 percent. Litter load was varied in these repetitive trials, because height and forest floor loading effects could not be entirely separated. By this process, two-thirds of visual height was chosen as the equivalent fuel-bed depth.

The mathematical model also required the input of only that amount of forest floor fuel (litter and duff) that will be consumed at the head of a spreading fire. This value is much easier to understand than to estimate. What is needed is the quantity of forest floor fuel which is actively involved in the spread of the fire. Experience and laboratory measurements imply that only the litter layer (not the fermentation or humus horizon) is actually consumed at the head of a free-burning fire. This estimate was upheld by repetitive trials of the spread model varying total duff loading in the fuel model. Moisture of extinction was held constant at 40 percent, and the two-thirds factor for fuel-bed depth was used. In this case, the model prediction of flame length was more sensitive to total duff loading than was spread rate. Weight of the litter layer proved the most reasonable approximation for the component of the forest floor involved in the propagation of a fire in this fuel complex and gave acceptable predictions of flame length (fig. 4).

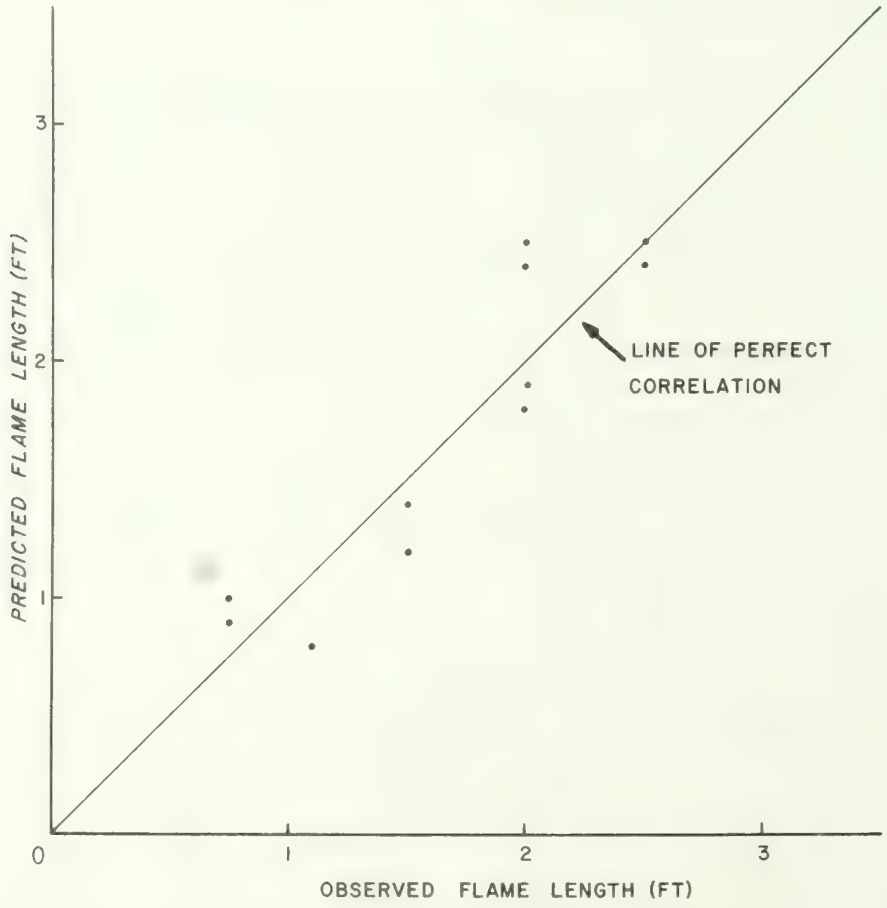

Figure 4.--Observed flame lengths for palmetto-gallberry backfires compared with predictions using weight of litter to represent the component of total forest floor involved in the fire front.

For predicting rates of spread of backfires, a windspeed of zero was entered in the model. There is ample evidence (Beaufait 1965; Hough 1968; Thomas 1971; Van Wagner 1968; Anderson and others 1966) that wind has little effect on the rate of spread of backfires. Figure 5 compares predicted (zero windspeed) and observed rates of spread for the 11 field plots with the most complete data. The dependence upon windspeed of the rate of spread and flame length in the palmetto-gallberry type was derived from the basic spread model, as described in a later section.

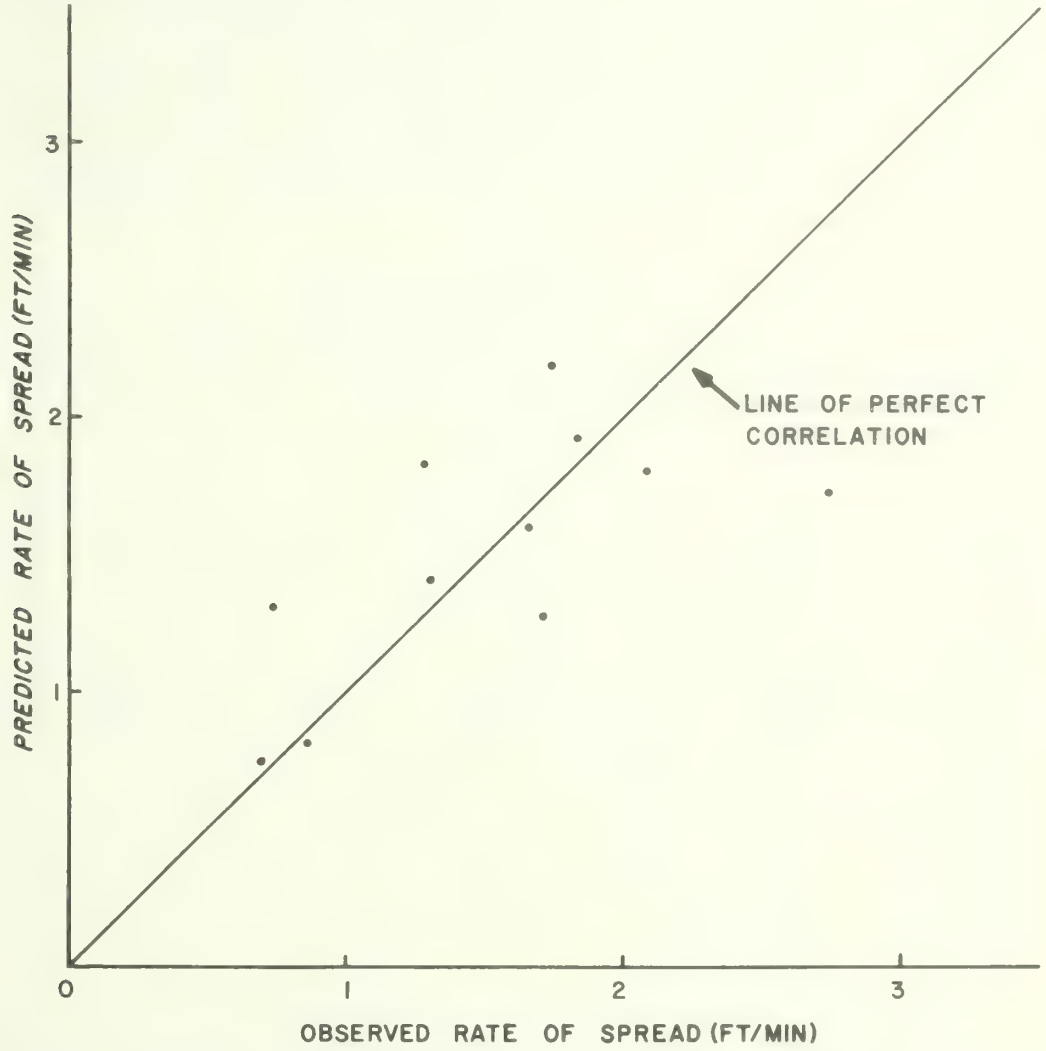

Figure 5.--Observed rate of spread for palmetto-gallberry backfires compared with predictions using model output at zero windspeed.

RESULTS AND DISCUSSION

Fuel Model Development

Averages and standard deviations of fuel descriptors were computed for most species by size class and fuel condition (live or dead). The values (table 23), based on all available laboratory measurements, are presented here to give the reader an idea of variability within and between species. Using these average values as the best estimates for each species, fuel condition, and size class, we then computed the contribution of each species to the plot or stand

Table 23.--Physical and chemical characteristics of the palmetto-gallberry fuel complex by species, fuel condition, and size class

Species or type and condition size class	Low heat value		Particle density		Mineral content		Effective mineral content		Surface area/volume	
	Mean	S.D.[1]	Mean	S.D.[1]	Mean	S.D.[1]	Mean	S.D.[1]	Mean	S.D.[1]
	Btu/lb		lb/ft^3		lb/lb		lb/lb		ft^2/ft^3	
Saw palmetto:										
Live < ¼" [2]	8,122	± 551	50.3	± 1.9	0.047	± 0.005	0.013	± 0.005	--	--
Live foliage	8,100	± 50	50.1	± 3.8	0.034	--	--	--	2,196	± 173
Live stem < ¼	--	--	53.9	± 3.3	--	--	--	--	409	± 77
Live stem ¼-1"	7,767	± 132	54.7	± 2.5	0.021	± 0.004	0.015	± 0.004	238	± 43
Gallberry:										
Live < ¼" [2]	8,430	± 590	43.8	± 1.6	0.023	± 0.006	0.020	± 0.002	--	--
Live foliage	8,843	± 50	37.4	± 3.5	0.021	--	--	--	2,593	± 414
Live stem < ¼"	--	--	47.0	± 1.6	--	--	--	--	447	± 92
Live stem ¼-1"	8,350	± 219	44.1	± 1.9	0.013	± 0.005	0.010	± 0.004	141	± 34
Mixed shrubs:										
Live < ¼" [2]	8,356	± 277	44.9	± 4.4	0.020	± 0.009	0.016	± 0.003	--	--
Live foliage	8,267	± 75	35.6	--	0.028	--	--	--	2,154	± 469
Live stem < ¼"	--	--	47.2	--	--	--	--	--	833	± 197
Live stem ¼-1"	--	--	42.3	--	--	--	--	--	153	--
Herbaceous:										
Live < ¼" [2]	7,898	± 175	34.7	± 3.8	0.045	± 0.006	0.014	± 0.006	2,881	± 498
Live foliage	7,850	± 50	--	--	0.028	--	--	--	--	--
Saw palmetto:										
Dead < ¼" [2]	8,546	± 298	26.3	± 2.3	0.039	± 0.012	0.008	± 0.010	--	--
Dead foliage	8,408	--	31.6	± 1.0	--	--	--	--	1,994	± 214
Dead stem < ¼"	--	--	27.9	± 2.5	--	--	--	--	263	± 37
Dead stem ¼-1"	--	--	28.4	± 4.5	--	--	--	--	169	± 2
Gallberry:										
Dead stem < ¼"	8,270	--	39.8	± 2.1	0.014	--	0.009	--	404	± 52
Dead stem ¼-1"	--	--	38.4	--	--	--	--	--	136	--
Mixed shrubs:										
Dead < ¼" [2]	8,035	± 441	29.6	± 2.6	0.036	± 0.017	0.010	± 0.020	1,952	± 539
Dead ¼-1"	8,167	± 335	27.4	± 4.3	0.013	± 0.002	0.006	± 0.002	159	± 39
Herbaceous:										
Dead foliage	7,367	± 50	--	--	0.054	--	--	--	1,968	± 121
Slash pine:										
Litter (L&F) < ¼" [2]	8,592	± 138	30.4	± 3.2	0.036	± 0.016	0.012	± 0.016	1,729	± 237
Litter (L) foliage	8,753	± 50	--	--	0.021	--	--	--	1,883	± 229
Litter (F) foliage	8,498	± 55	--	--	0.028	--	--	--	1,900	± 222
Litter ¼-1"	8,393	± 119	27.0	± 4.2	0.018	± 0.008	0.011	± 0.004	107	± 23
Litter 1-3"	8,057	± 242	28.4	± 7.2	0.018	± 0.010	0.008	± 0.012	32	± 15
Litter (H) < ¼"	7,878	± 461	24.5	± 2.2	0.098	± 0.023	0.017	± 0.021	--	--
Longleaf pine:										
Litter (L&F) < ¼" [2]	8,757	± 213	31.7	± 2.2	0.032	± 0.005	0.013	± 0.005	1,851	± 45
Litter ¼-1"	--	--	30.2	± 7.4	--	--	--	--	104	± 22
Litter 1-3"	--	--	32.5	± 7.4	--	--	--	--	19	--
Litter (H) < ¼"	8,031	--	25.0	--	0.082	--	0.013	--	--	--

[1]Standard deviation.
[2]Samples contain foliage and stems < ¼ inch in diameter; all sample sizes are in inches.

value. For example, the fraction of the total live-foliage weight made up of live palmetto foliage was computed. This fraction was used as a weighting factor for each model input variable, allowing us to compute the contribution of live palmetto foliage to the values representing all live foliage occurring on the plot. In this way, plots that had most of the fuel weight in one species had values of particle density, heat value, and the other fuel characteristics closest to that species.

We looked for variation in the weighted average values that might be related to age of rough, which ranged from 1 to 22 years on the fuel sampling plots. Values of the fuel descriptors for each forest stand, by fuel condition and size class, were plotted against age of rough. Other than loading, which is determined separately, the only factor that seemed to be age related was the S/V ratio for the 0- to $\frac{1}{4}$-inch live-fuel class. Other fuel characteristics were unrelated to age of rough. It was decided that the best value for each size class

and fuel condition would be the average of all plot values. These values and their standard deviations are presented in table 24.

The greatest differences in S/V ratios were obviously between, rather than within, size classes for different fuel conditions. For this reason, all values were combined to arrive at a single surface area to volume ratio for each of the three size classes being used in the model. Major differences in particle density and silica-free ash were between the live and dead components. Differences in low heat value and total ash content occurred between live and dead fuels and between size classes of fuels, but these differences were not considered significant. In an effort to reduce the number of input values needed for the spread model, representative values were selected for each fuel condition and size class under consideration (table 25). This approach greatly reduces the amount of field work required to get input data for predictions, while reducing precision only slightly.

Table 24.--Physical and chemical characteristics averaged over all plots by major fuel conditions and size classes: palmetto-gallberry fuel complex

Fuel condition and size class	Low heat value		Particle density		Total ash		Silica-free ash		Surface area/volume	
	Mean	S.D.[1]	Mean	S.D.[1]	Mean	S.D.[1]	Mean	S.D.[1]	Mean	S.D.[1]
	Btu/lb		lb/ft^3		- - - - - - lb/lb - - - - - -				ft^2/ft^3	
Aerial fuels:										
Live foliage	8,175	± 92	45.5	± 3.4	0.041	± 0.007	0.015	± 0.007	2,322	± 211
Live 0-¼"	8,302	± 66	49.6	± 1.5	0.032	± .005	0.017	± .006	467	± 98
Live ¼-1"	8,166	± 179	47.4	± 3.2	0.016	± .002	0.012	± .001	166	± 35
Dead foliage	8,299	± 256	30.7	± 1.0	0.038	± .001	0.009	± .002	1,999	± 359
Dead 0-¼"	8,229	± 184	31.9	± 2.7	0.031	± .006	0.010	± .006	322	± 60
Dead ¼-1"	8,167	± 335	27.4	± 4.3	0.013	± .002	0.006	± .002	151	± 37
Surface fuels:										
Dead L layer	8,592	± 138	30.4	± 3.2	0.036	± .016	0.012	± .016	1,806	± 230
Dead 0-¼"	8,229	--	31.9	--	0.031	--	0.010	--	325	± 52
Dead ¼-1"	8,393	± 119	27.0	± 4.2	0.018	± .008	0.011	± .004	107	± 23

[1]Standard deviation.

Table 25.--Physical and chemical values for the palmetto-gallberry complex used as input to the fire behavior model

Fuel condition and size class	Low heat value	Particle density	Total ash	Silica-free ash	Surface area/volume
	Btu/lb	lb/ft^3	- - lb/lb - -		ft^2/ft^3
All live fuels	8,300	46	0.030	0.015	
All dead fuels	8,300	30	0.030	0.010	
All foliage					2,000
All 0-¼" stems					350
All ¼-1" stems					140

Fuel loading by size class was highly correlated with age of rough, height of the understory fuel, percentage of palmetto on the area, and basal area of the overstory timber stand. These characteristics were used to develop predicting equations for each of the needed combinations of fuel condition and size class.[10] These equations (table 26) and the characteristics measured in the forest stand were then used to compute the weight by size class of each fuel component.

Table 26.--Equations used to estimate fuel loading (lb/ft^2 on dry-weight basis) of palmetto-gallberry fuel components used as input to the fire behavior model

Fuel component dry weight	Regression equation
Live foliage	$-0.0036 + 0.00253(AR) + 0.00049\ (PPal) + 0.00282(HT^2)$
Live 0-¼"	$+0.00546 + 0.00092(AR) + 0.00212(HT^2)$
Live ¼-1"	$-0.02128 + 0.00014(AR^2) + 0.00314(HT^2)$
Dead foliage	$+0.00221(AR^{0.51263})\ \exp\ (0.02482\ (PPal))$
Dead 0-¼"	$-0.00121 + 0.00379(\ell n\ AR) + 0.00118(HT^2)$
Dead ¼-1"	$-0.00775 + 0.00021\ (PPal) + 0.00007(AR^2)$
L layer	$(0.03632 + 0.0005336(BA))\ (1 - (0.25)^{AR})$

where:

AR = age of rough, years

PPal = coverage of area by palmetto, percent

HT = height of understory, feet

BA = basal area of overstory, square feet per acre.

Since we wanted to include the effects of changes in live-fuel moisture content on fire behavior, we developed a seasonal curve from biweekly measurements of moisture content of palmetto and gallberry plants. The major seasonal features of this curve were low-fuel moisture content in winter and early spring, followed by a high-moisture content in late spring and summer. We decided to enter only these major differences in the fire behavior model. In this way, live-fuel moisture content values for only two periods of the year had to be used. The live-fuel moisture contents were 130 percent for foliage and 105 percent for stemwood in summer, and 105 percent for foilage and 75 percent for stemwood in winter.

Moisture content of the dead-fuel components also had to be estimated. The original intent was to use the National Fire Danger Rating System (NFDRS)

[10] See footnote 8.

(Deeming and others 1972) 1-hour timelag tables for the L layer and standing dead foliage, and the 10-hour tables for the dead $\frac{1}{4}$- to 1-inch fuels. To reduce the number of moisture content values needed for model input, it was assumed that the forest floor L layer and standing dead foliage were the major carriers of the fire front. The $\frac{1}{4}$- to 1-inch material made up a small part of the total dead-fuel weight and had little influence on spread rate. This size class was assigned the same moisture content value as the other dead fuels.

Actual moisture content of the L layer on field plots ranged from 9 to 33 percent while moisture content predicted by the NFDRS 1-hour tables ranged only from 5 to 11 percent. The 10-hour tables also gave an inadequate range of moisture contents, 6 to 14 percent, for the L layer.

In addition to the 1-hour timelag tables, that proved inadequate, two other methods for estimating dead-fuel moisture content were considered. An empirical relationship between relative humidity, days since rain, and L layer moisture content was reported by Hough (1968), but moisture added by precipitation was not considered. Analysis of the NFDRS components using weather data from the Southeastern United States showed that 100-hour timelag fuel moisture varied from 10 percent (occurring on the 6th day following rain) to 28 percent (immediately after rain).[11] This range is approximately the same as that measured in L layer samples from the field for similar weather conditions. Based on this analysis, we recommend that the NFDRS 100-hour timelag fuel moisture tables be used to estimate dead-fuel moisture content in the palmetto-gallberry model.

Rate of Spread and Flame-Length Estimates

With the relationships outlined, a palmetto-gallberry fuel complex can be completely described by specifying the following:

1. Age of rough (years since last burn)
2. Height of understory (visual height)
3. Percent coverage by palmetto
4. Basal area of overstory stand
5. Summer or winter burn
6. Moisture content of dead fuels.

The first three variables define the standing understory fuel loadings by size class, through predictive relationships. The overstory stand density (basal area) is an indicator of tree biomass and hence of foliar litter production rate. This variable, in conjunction with the age of the rough, permits the computation of litter accumulation (pine needles) on the site. Live-fuel moisture content depends upon whether the burn is in summer or winter. The moisture content of the dead fuels varies widely, depending upon local, recent weather history, and is best estimated using NFDRS 100-hour timelag values.

[11] Paul, James T. 1973. Analysis of fire danger in southeastern Georgia. Ph. D. diss., Univ. Ga., Athens.

For most areas of the South in which palmetto-gallberry associations are important understory fuels, the terrain is relatively flat. Therefore, the slope was assumed to be zero in the rate of spread model. Windspeed is also an important variable; it is treated separately at the end of the procedure.

Backfire Predictions

To simplify computations, a representative range of values was chosen for each of the variables listed, and the results of the computations at zero windspeed are shown in tables 1-18. The range of variable values was chosen to span the spectrum of conditions normally found:

Age of rough: 1, 2, 3, 4, 5, 8, 15, and 25 years

Height of understory: 1, 2, 3, 4, 5, and 6 feet

Percent covered by palmetto: 15 percent (sparse), 50 percent (broken), and 85 percent (continuous)

Basal area of overstory: 30 (low), 70 (medium), and 110 (high) ft^2/acre

Moisture content of dead fuels: 5, 10, 15, 20, and 30 percent.

Backfire rates of spread were computed with the current version of Rothermel's (1972) model. Flame lengths were computed from Byram's (1959) formula:

$$L = 0.45(I)^{0.46}$$

where

L = flame length in feet

I = Byram's fireline intensity in Btu/s/ft.

Using the "reaction intensity," or rate of heat release per unit area at the fire front, I_R (Btu/ft^2/min), available from Rothermel's model, the rate of spread, R (ft/min), and an estimate of the flame residence time, τ (min), Byram's intensity can be calculated (Albini 1976b):

$$I = (I_R \cdot R \cdot \tau)/60.$$

The residence time was computed from a relationship developed by Anderson (1969), based on the characteristic surface area/volume ratio of the modeled fuel bed where τ (min) = $384/\tilde{\sigma}$ (ft^{-1}).

Head Fire Predictions

According to Rothermel's (1972) model, the principal effect of wind on a free-burning fire is to increase the efficiency of heat transfer from burning fuel to unignited fuel, with accompanying increase in rate of spread but little or no change in reaction intensity. The formula given by Rothermel for the wind-driven rate of spread, R, is:

$$R = (1 + \phi_W)R_O$$

with R_o the rate of spread under no wind, and the "wind factor" ϕ_w a function of fuel-bed packing ratio, β, and the characteristic surface area/volume ratio of the modeled fuel complex, denoted by $\tilde{\sigma}$. Packing ratio is the fraction of the fuel-bed volume which is filled with fuel particles, and $\tilde{\sigma}$ is a weighted average of the surface area/volume ratios of the individual fuel particles. The equation for ϕ_w was developed from laboratory data and is complex but straightforward:

$$\phi_w = AU^B$$

where

U = windspeed, ft/min, at midflame height

$B = 0.02526\ \tilde{\sigma}^{0.54}$

$A = C(\beta_o/\beta)^E$

$C = 7.74 \exp(-0.133\ \tilde{\sigma}^{0.55})$

$E = 0.715 \exp(-0.000359\tilde{\sigma})$

$\beta_o = 3.348/\tilde{\sigma}^{0.8189}$

and $\tilde{\sigma}$ is measured in units of ft^{-1}.

Note that two quantities ($\tilde{\sigma}$ and β) describe the effects of windspeed on head fires. The values of these variables were systematically reviewed for the range of fuel beds considered, with an eye to simplifying this computation. The range of values indeed allows simplification, since

$$1.42 \leq B \leq 1.52,$$

$$0.351 \leq E \leq 0.383,$$

$$2.26 \times 10^{-4} \leq C\beta_o^E \leq 3.66 \times 10^{-4}.$$

Using midrange values for these parameters, and converting units from ft/min to mi/h for windspeed, we found a formula which approximates the complete expression to within ± 25 percent:

$$\phi_w \doteq 0.2165\ (U(\text{mi/h}))^{1.47}/\beta^{0.367}.$$

Thus, by classifying each modeled fuel bed in terms of its packing ratio, β, a set of "categories" could be established, with a representative packing ratio for each. Tables 19-21 were prepared to show in what category each fuel bed falls. Once this category is determined, figures 1 and 2 provide appropriate multiplying factors for adjusting the zero-wind rate of spread and flame length to get the head fire rate of spread and flame length. The use of these tables and graphs was illustrated in the first part of this paper. Figure 6 shows the influence of wind and fuel moisture on predicted head fire rate of spread for typical palmetto-gallberry stand conditions.

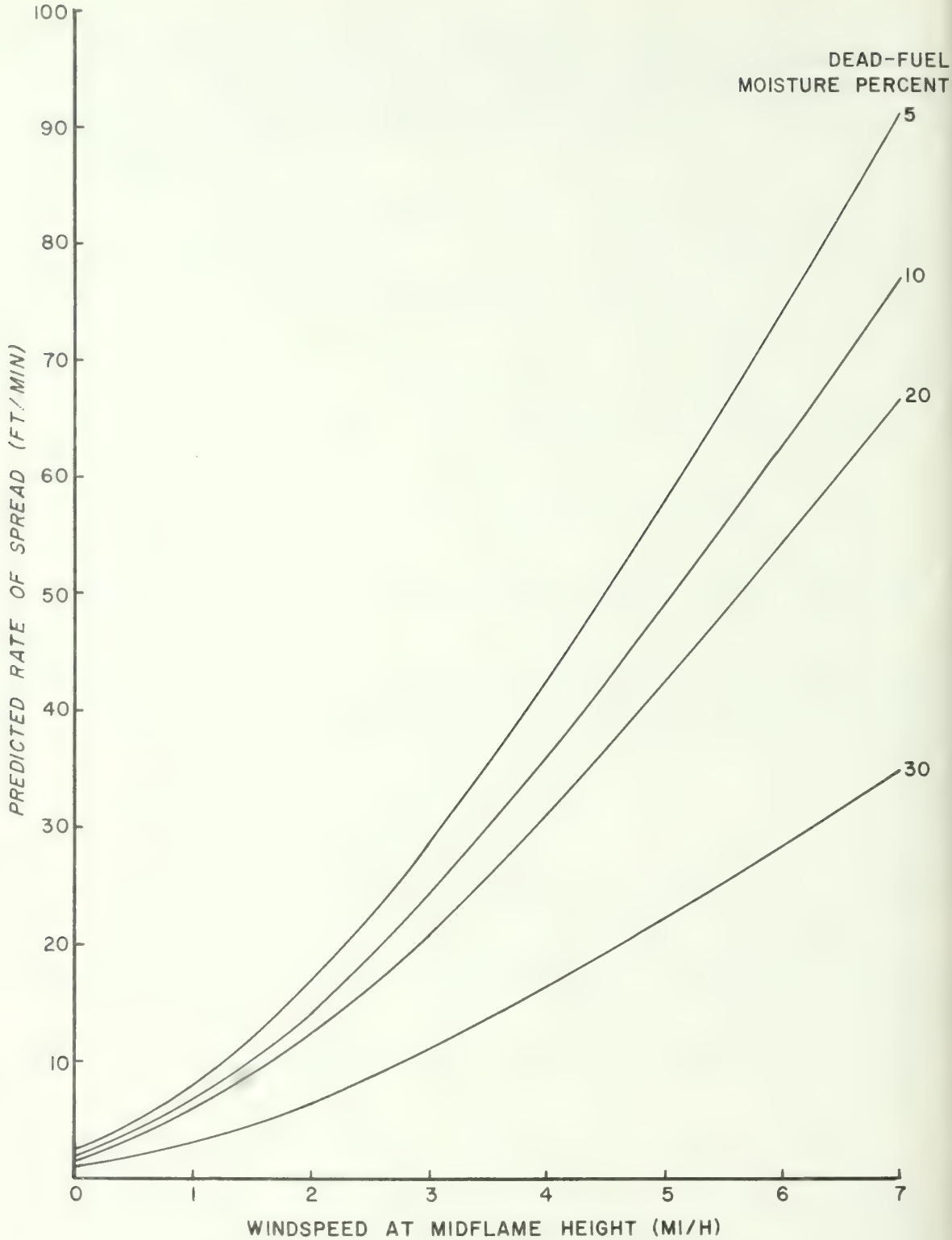

Figure 6.--Influence of wind and fuel moisture content on predicted rate of fire spread in an average palmetto-gallberry association.

Stand conditions: overstory basal area = 70 ft^2/acre, age of rough = 8 yr, understory height = 3 ft, and palmetto coverage = 50 pct

Fire Intensity

The intensity of a free-burning fire, as determined by Byram's (1959) formula, provides a ready measure of the severity of the fire. For hazard-reduction burns in the palmetto-gallberry type, intensities between 20 and 80 Btu/s/ft are satisfactory (Hough 1968). Hodgson (1968) recommends a maximum value of 100 Btu/s/ft for controlled burning, and suggests that at about 600 Btu/s/ft a surface fire may become uncontrollable. Serious spotting has been noted at intensities between 500 and 1,200 (Hodgson 1968; Kiil 1975), and intensities of 2,000 to 3,000 have been associated with crowning (Van Wagner 1968). The maximum height of lethal scorching in coniferous crowns has also been directly related to Byram's intensity (Van Wagner 1973).

In the tables and graphs presented in Part I, we used flame length as a measure of intensity, since this phenomenon is directly observable. But the flame lengths were calculated using Byram's (1959) formula, given earlier. The intensity of a fire can be estimated from its observed or calculated flame length.

Test of Model Output

To provide a general idea of how predicted and actual rates of spread compare, rate-of-spread data (not used to develop model) from past fires in stands of palmetto-gallberry were obtained from the files at the Southern Forest Fire Laboratory. Spread rates were from head and backfires on plots ranging from 0.5 to 2 acres. Variables such as basal area, percent palmetto, and height of the understory were not available for every individual plot. Therefore, the average stand conditions that prevailed in the experimental area were used in several cases. Even though variation in stand conditions was known to occur between individual test plots, the discrepancies were not considered great enough to disqualify the comparisons. For this particular set of data, rates were slightly underestimated (fig. 7). However, most predictions did not differ from observed values by more than ± 8 ft/min for head fires and ± 1 ft/min for backfires.

In predicting rate of spread from the original data, it was noted that L layer fuel moisture content was often much higher than that estimated at the nearest fire danger rating station. Also, it was noted that windspeed within the stand was half or less the windspeed measured at the fire danger rating station. For our predictions, we measured windspeed in the stand near the fire, and for best predictions a user should do the same.

If it is inconvenient to measure windspeed, a value can be estimated from the windspeed at the nearest fire danger rating station. The relationship between windspeed at a 20-foot tower in the open and windspeed in a forest stand depends on a number of factors (USDA Forest Service 1970). In slash pine stands it is influenced by basal area and height of the stand (Cooper 1965). The tables presented by Cooper could be used to convert windspeed measured at a nearby danger station into a rough estimate of windspeed within a stand.

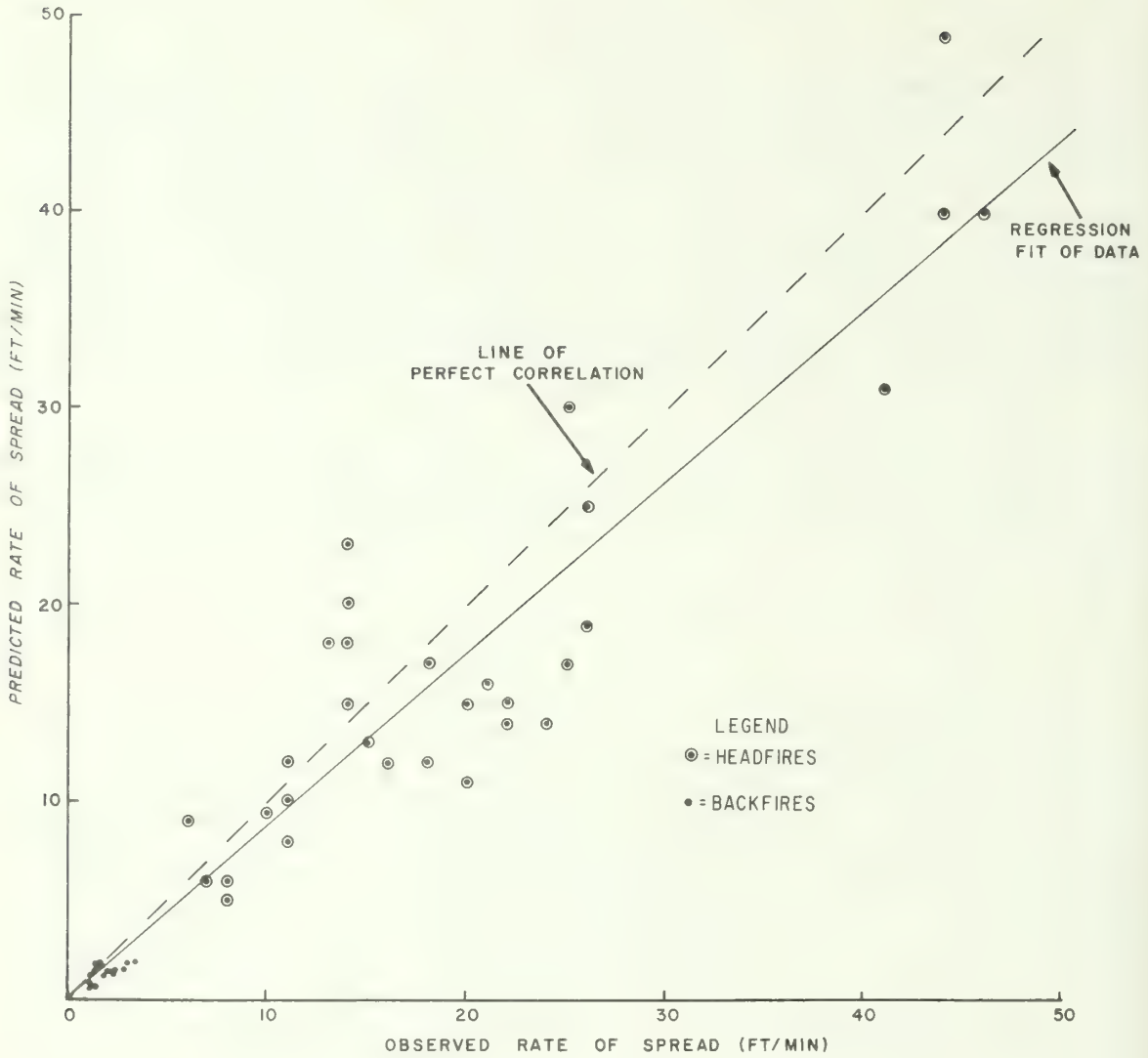

Figure 7.--Relationship between observed and predicted rates of spread for winter fires.

CONCLUSIONS

The material presented in this paper should be useful to forest fire managers. It is especially well suited for prescribed burning, because rate of spread, fire intensity, and flame length can be predicted before the fire is lit. Fire suppression forces can also use the tables and curves to estimate how fast a wildfire will spread in a particular fuel under actual or forecast weather conditions. For instance, the Florida Division of Forestry (1973) published guidelines for forest fire suppression tactics. The section on palmetto-gallberry fuel types indicated that there was not enough information on fire behavior in palmetto-gallberry fuels to be able to specify suppression tactics adequately. We hope that the spread and intensity information provided in this publication will fill this need.

When applying the procedures, the most accurate estimates of rate of spread will result when actual dead-fuel moisture content and midflame windspeed within the stand are measured at the time of burning. If on-site measurements cannot be made, other sources of the needed data must be used and the losses in precision, already discussed, must be accepted.

The user of this information must again be cautioned about the limitations of predictions. The estimated rates of spread do not apply to high-intensity wildfires where spotting and crowning are influencing fire behavior. Spread values are most reliable for backfires and low-intensity head fires, which are typical of prescribed burns and the initial stages of wildfires.

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Throughout this paper, values are in English units because these are still most commonly used in forestry in the United States. Factors for converting from English to metric units are provided below:

To convert from	To	Multiply by
acre	hectare	0.4047
Btu/pound	Joule/gram	2.3244
Btu/second/foot	kilowatt/meter	3.4592
foot	meter	0.3048
$foot^2$/acre	$meter^2$/hectare	0.2296
inch	centimeter	2.5400
miles/hour	kilometer/hour	1.6093
pound	kilogram	0.4536
$pound/foot^2$	$kilogram/meter^2$	4.8823
$pound/foot^3$	$kilogram/meter^3$	16.0185
tons/acre	tonne/hectare	2.2417

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1978 Predicting fire behavior in palmetto-gallberry fuel complexes. U.S. Dep. Agric. For. Serv., Res. Pap. SE-174, 44 p. Southeast. For. Exp. Stn., Asheville, N. C.

Rate of spread, fireline intensity, and flame length can be predicted with reasonable accuracy for backfires and low-intensity head fires in the palmetto-gallberry fuel complex of the South. Age of rough, height of understory, percent of area covered by palmetto, basal area of overstory, season of year, moisture content of dead fuels, and midflame windspeed must be known to make predictions.

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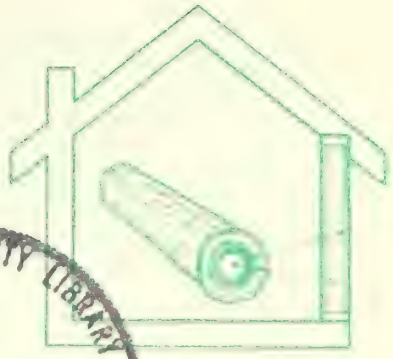

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COM-PLY 8 REPORT

STRUCTURAL PERFORMANCE OF NAILED JOINTS WITH COM-PLY STUDS

COOPERATIVE RESEARCH

STRUCTURAL PERFORMANCE OF NAILED JOINTS WITH COM-PLY STUDS

by

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Athens, Georgia

Cooperative Research by

U.S. Department of Agriculture, Forest Service

Southeastern Forest Experiment Station

and

U.S. Department of Housing and Urban Development

Division of Energy, Building Technology

and Standards

PREFACE

This report is one of a series on the possibilities of producing house framing and structural panels with particleboard cores and veneer facings. These COM-PLY or composite materials were designed to be used interchangeably with conventional lumber and plywood in homes. Research on structural framing is presently limited to COM-PLY studs but will be extended to include larger members such as floor joists.

In 1973, the home-building industry faced a shortage of lumber and plywood and consequent rising prices. Both industry and government recognized that this situation was not a temporary problem, and that long-range plans for better using the Nation's available forest resources would be necessary.

The USDA Forest Service and the U.S. Department of Housing and Urban Development accelerated cooperative research on ways to utilize the whole tree. They concentrated on composite wood products made with particleboard and veneer as a way of using not only more of the tree stem, but also using less desirable trees and a greater variety of tree species than would conventional wood products. The particleboard which comprises a large portion of the COM-PLY stud is made from ground-up wood that comes from forest residues, mill residues, or low-quality timber. Thus, such composites could greatly increase the amount of lumber and plywood available for residential construction, our major use of wood, without eroding the Nation's timber supply.

Research on composite wall framing was performed by the Wood Products Research Unit, Southeastern Forest Experiment Station, Athens, Georgia. The American Plywood Association cooperated in these studies by designing and testing composite panel products that are interchangeable with plywood. Both types of products have been incorporated in demonstration houses.

Included in this series will be reports on structural properties, durability, dimensional stability, strength, and stiffness of composite studs. Other reports will describe the overall project, compare the strength of composite and solid wood studs, suggest performance standards for composite studs, and provide construction details on houses incorporating such studs. Still others will explore the economic feasibility of manufacturing composite studs and panels and estimate the amount and quality of veneer available from southern pines. These reports, called the COM-PLY series, will be available from the Southeastern Forest Experiment Station and the U.S. Department of Housing and Urban Development.

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STRUCTURAL PERFORMANCE OF NAILED JOINTS WITH COM-PLY STUDS

Abstract.--Strength and rigidity of nailed joints between COM-PLY studs and wall plates or wall sheathing were sufficient for use in framing walls of houses, exceeding the minimums currently accepted in conventional construction. In almost every test, such joints were stronger and more rigid than their counterparts with studs of solid spruce. Generally, nailed joints with COM-PLY studs varied less in strength than did those with spruce studs.

KEYWORDS: Nailed joint strength, wall-framing joints, nailed joint rigidity, toe-nailed joints, end-nailed joints, stud fastening, face-nailed joints.

To better utilize our Nation's timber resources and offset potential shortages of lumber for home building, the Wood Products Research Unit of the Southeastern Forest Experiment Station and the Department of Housing and Urban Development have developed a new composite product called the COM-PLY stud. This sandwich-type stud consists of a particleboard core with two veneer strips glued to each narrow edge (fig. 1).

Figure 1.--COM-PLY stud consisting of a particleboard core and veneer faces.

COM-PLY studs are designed for use as wall frames in houses (fig. 2). Because the joints of a house frame are often the weakest part of the structure, potential manufacturers, home builders, and building code officials must know the strength and rigidity of nailed joints with COM-PLY studs. They need to know whether such joints are strong and permanent enough to provide serviceable wall frames and whether they will perform as well as nailed joints with studs of solid wood. Furthermore, if composite studs are used in place of or in combination with conventional studs, builders must be able to space them the same distance apart as they do conventional studs and to fasten them with the same size nails without causing more or larger splits.

This paper reports the lateral and direct withdrawal strength of nailed joints with COM-PLY studs tested in accordance with the formulas in the Performance

Standards for such studs used in house framing (Blomquist and others 1976). Included are end-nailed and toe-nailed joints between wall plates and studs (fig. 3) and face-nailed joints between wall sheathing and studs (fig. 4). Nailed joints fabricated with spruce studs are included for comparison. Spruce studs were selected because they are representative of western softwoods (true firs, spruces, lodgepole pine) now being used in large volume by builders. Use of stronger species such as Douglas-fir or southern pines would set a higher standard for nailed joints than is now required by builders and building code officials.

Figure 2.--COM-PLY studs installed as wall framing in a house under construction.

MATERIALS

For the composite portion of the test specimens of nailed joints, researchers used COM-PLY studs fabricated in the laboratory. These studs had a core of 1-1/2-inch-thick, phenolic-bonded particleboard made in a factory. The manufacturer used air suspension to form the three-layered particleboard. Wood particles for the board were made from planer shavings, slabs, edgings, and other mill residues from southern pine.

The particleboard had an average density of 40 lb/ft^3, an internal bond of 75 lb/in^2, a modulus of elasticity (in plane of panel) of 300,000 lb/in^2, and a modulus of rupture of 3,400 lb/in^2. It contained 8 percent resin binder throughout the three layers.

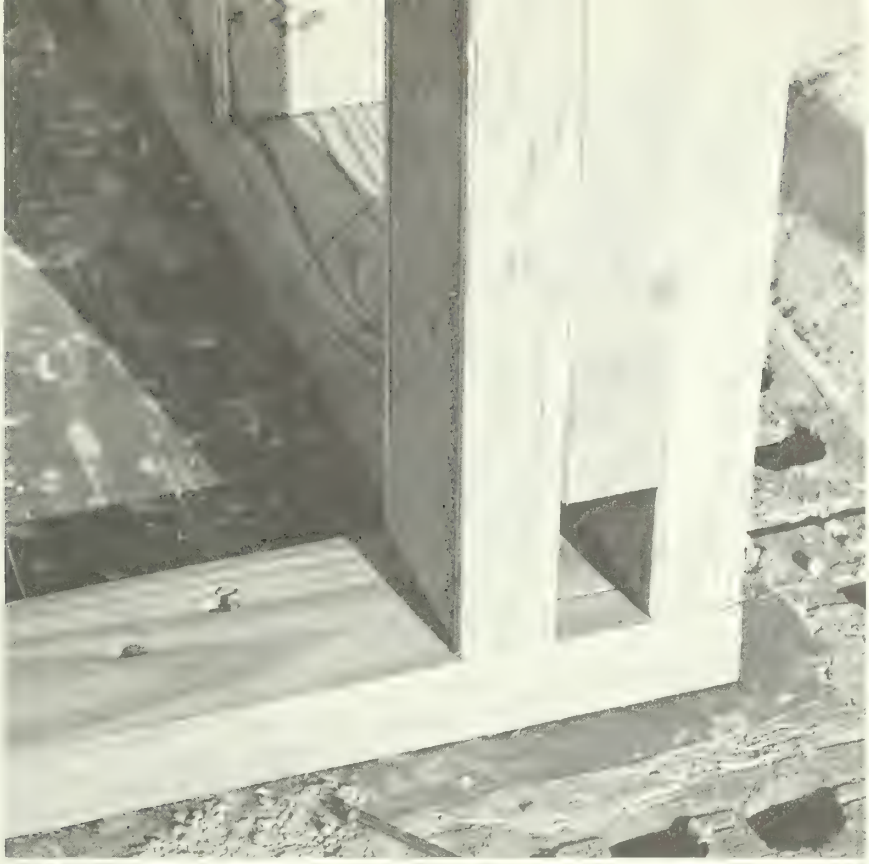

Figure 3.--End-nailed joint between COM-PLY stud and exterior wall plate.

Figure 4.--Face-nailed joint between COM-PLY stud and sheathing of insulation board.

Veneer strips of southern pine were rotary-cut and parallel-laminated to the 1-1/2-inch edges of the particleboard core. These veneer strips were 1/6 inch thick, 1-1/2 inches wide, and 96 inches long.

The laminating adhesive was a phenol-resorcinol resin that cures at room temperature and is typically used in structural laminated timbers. The spread rate of the mixed adhesive was 60 lb/Mft^2 of glueline for the veneer-to-veneer bonds and 100 lb/Mft^2 of glueline for the veneer-to-particleboard bonds.

When the COM-PLY studs were completed, they measured 1-1/2 inches thick, 3-1/2 inches wide, and 96 inches long. Researchers cut sections for the test specimens from these COM-PLY studs.

For the solid lumber in the test specimens, researchers randomly selected stud-grade spruce studs from stocks of local lumber dealers. Only those portions of the spruce studs that were straight and relatively free from knots and other defects were used in the specimens.

All COM-PLY and spruce studs used in the test specimens were conditioned to a constant weight under a controlled temperature of $70^{\circ} \pm 3^{\circ}$ F ($21^{\circ} \pm 2^{\circ}$ C) and a relative humidity of 60 $\pm$ 5 percent.

For stud-to-plate joints, researchers used 8d common nails for toe-nailing and 16d box nails for end-nailing. They used 8d common nails, 16d box nails, and drywall nails for tests of resistance to withdrawal from the face of the stud and 6d common nails for lateral load tests on joints between sheathing and the veneer face of the stud.

GENERAL PROCEDURES

Until the Performance Standards for COM-PLY studs were developed by Blomquist and others (1976), no one had ever devised test procedures specifically for evaluating nailed joint strength of such studs. In devising the Performance Standards, these researchers used procedures outlined in Scholten and Molander (1950) and in ASTM D 1761-74 (ASTM 1975b) for evaluating nailed joints of solid wood studs.

In each test, researchers evaluated 10 specimens of each type of joint tested. They tested all specimens within 4 hours after fabrication. Each group was tested for joint deformation and ultimate load, i.e., the point when deformation occurs at an increasing rate per unit of time with no increase in load or when the test specimen has collapsed.

After completing tests on each group of joints, researchers computed the average and the standard deviation for ultimate loads of the group according to accepted statistical procedures. They also computed the average and the standard deviation for joint deformations of each group. The calculated averages and standard deviations were used to compute the adjusted values for loads and deformations according to the formulas given in the Performance Standard for strength of nailed joints. In computing adjusted values for joint deformations, only stud-to-plate joints were evaluated because excessive deformation in such joints can seriously affect the appearance of a house.

The following formula was used to compute the adjusted value for load:

$$P = \left[\bar{p} - \frac{t_{0.05} S}{\sqrt{N}} - t_{0.05} S \right] \frac{1}{F_s F_t}$$

where:

P = adjusted value for load in pounds per joint

$\bar{p}$ = one-half of the average ultimate test load in pounds

$t_{0.05}$ = statistical t at 0.05 confidence level for N - 1 degrees of freedom

S = standard deviation of ultimate joint loads (one-half of ultimate test load) in pounds

N = number of test specimens

F_s = factor of safety; use 1.5

F_t = adjustment for the ratio of the duration of the test load to the duration of the service load. In this case, the service load is assumed to be the wind load, and the factor for the duration of this load is 1.33. If the test load is applied over an average period of 4 minutes, the factor for the duration of this load is 1.65. In this example, the test load is applied faster than the service load; therefore, the adjustment factor is 1.65/1.33 or 1.24 (Hunt and others 1973; ASTM 1975a).

The following formula was used to compute the adjusted value for joint deformation:

$$D = \bar{d} + \frac{t_{0.05}S}{\sqrt{N}}$$

where:

D = adjusted value for joint deformation of stud relative to plate, in inches

$\bar{d}$ = the average joint deformation on N test joints when a 160-pound joint load (320-pound test load) is applied to the joint

$t_{0.05}$ = statistical t at 0.05 confidence level for N - 1 degrees of freedom

S = standard deviation of joint deformations under a 160-pound joint load (320-pound test load)

N = number of specimens

These formulas from the Performance Standard were designed to determine safe loads and safe deflections for a group of studs by penalizing materials with wide variations in strength and stiffness. Thus, when ultimate strength and stiffness values vary widely, they are reduced more by the formulas for computing the adjusted loads and deflections than if the strength and stiffness values are relatively uniform.

LATERAL LOAD ON JOINTS BETWEEN WALL PLATE AND END OF STUD

METHODS

Scientists used the lateral load resistance and rigidity of joints between studs and plates to simulate wind loading perpendicular to a wall surface.

Loading of a test specimen is shown in figure 5. To prepare the specimens, researchers nailed a 16-inch length of stud to a 7-inch length of spruce 2 x 4 plate material. To make end-nailed specimens, they drove two 16d box nails through the plate and into the end of the stud. Each nail was spaced 7/8 inch from the

edge of the plate. To make the toe-nailed specimens, they drove two 8d common nails into each wide face of the stud. These nails were positioned 7/8 inch from the outer edge of the stud, 1 inch from the end of the stud, and at a 30° angle to the face of the stud.

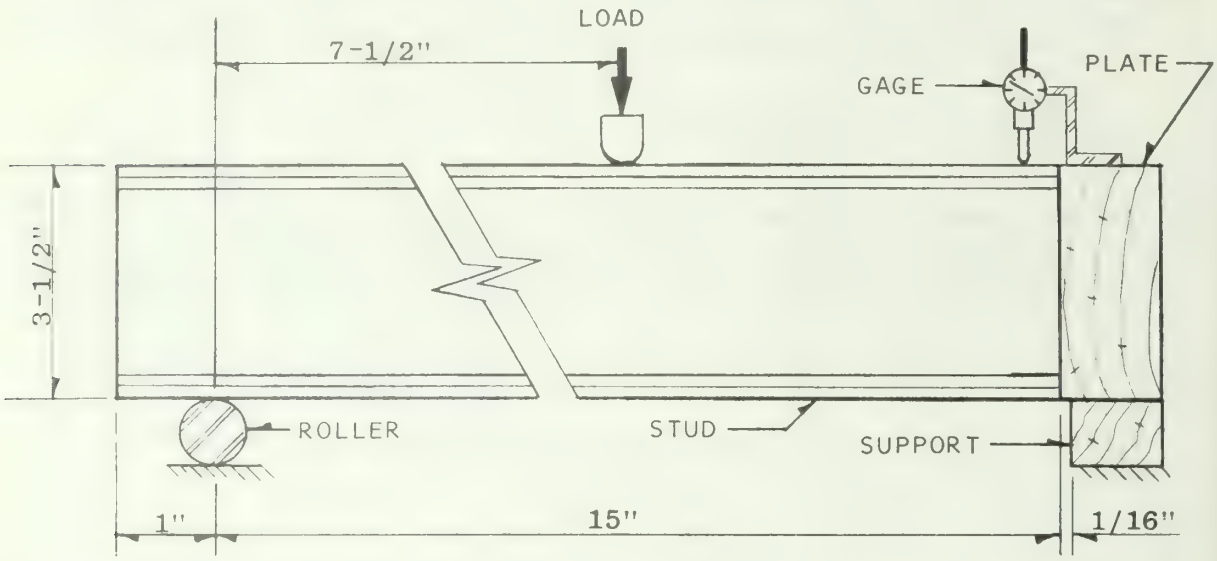

Figure 5.--Lateral loading of test specimen of a stud-to-plate joint.

The specimens were then placed in a universal testing machine (fig. 6). The machine applied the load continuously at a rate of 0.012 inch per minute until ultimate load occurred. Technicians recorded the ultimate load to the nearest pound. With a dial indicator incremented to 0.001 inch, they also measured joint deformation between the stud and the plate at deformation increments of 0.005 inch up to a deformation of 0.030 inch and at increments of 0.010 inch up to a deformation of 0.100 inch.

RESULTS

Table 1 shows the results of the lateral load tests on joints between a spruce plate and the end of a spruce or COM-PLY stud. Such joints should safely carry a 160-pound adjusted load to be acceptable for use in housing, according to the Performance Standard. COM-PLY studs had an adjusted load of 331 pounds for toe-nailed joints and 199 pounds for end-nailed joints. Spruce studs had adjusted loads of 166 pounds for toe-nailed joints and 161 pounds for end-nailed joints. Thus, the adjusted loads for nailed joints with COM-PLY studs were greater than those for joints with spruce studs, and the COM-PLY joints had a safe joint strength well above the minimum acceptable load. In addition, the variation from the average strength, as indicated by the standard deviations, was less for joints with COM-PLY studs than for joints with spruce studs.

End-nailed joints with spruce studs had a higher average ultimate load than those with COM-PLY studs, but they also had a larger standard deviation in ultimate load. In fact, both types of joints with COM-PLY studs had less deviation in ultimate load than their spruce counterparts. Therefore, their adjusted loads were greater than those of joints with spruce studs.

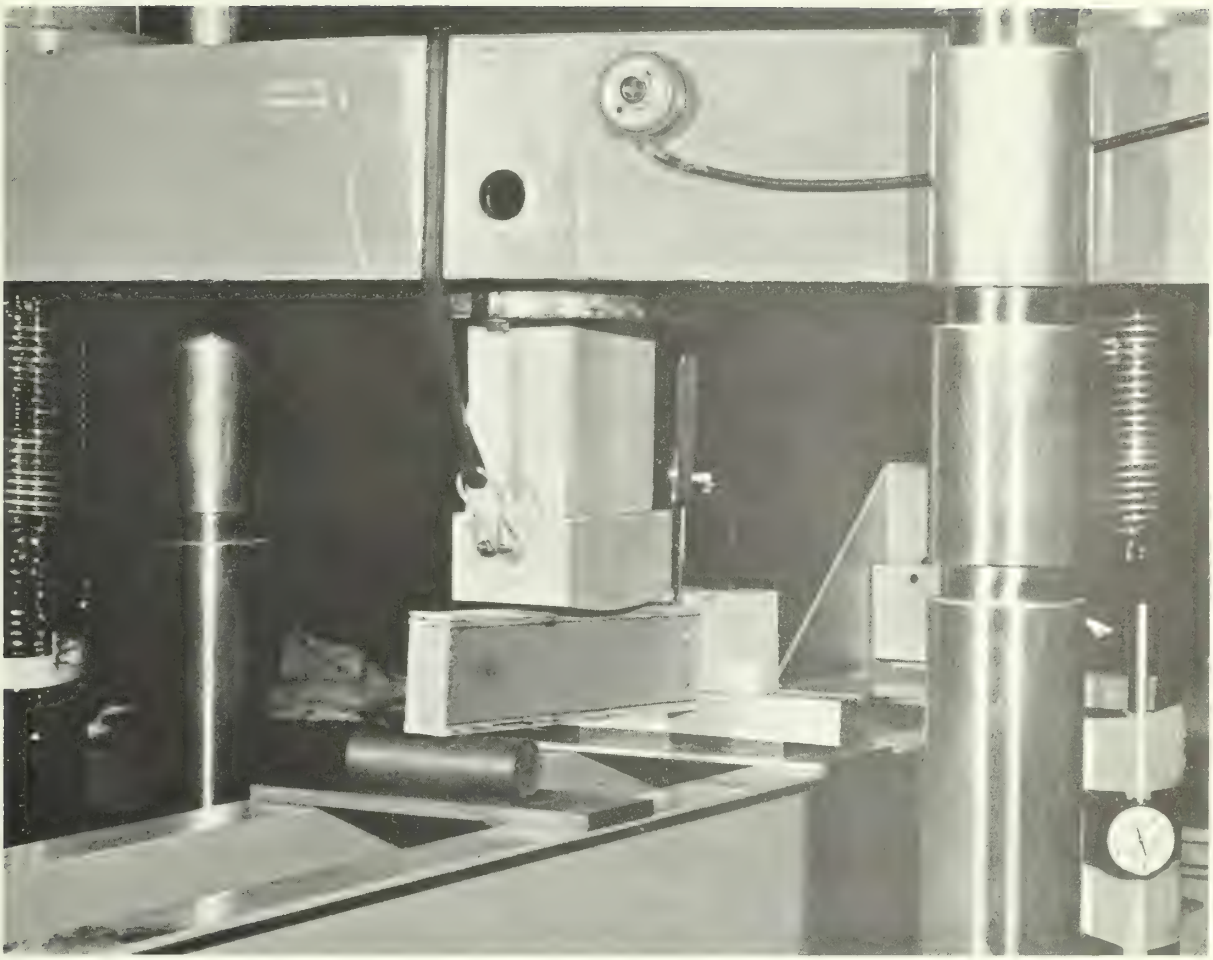

Figure 6.--Specimen being tested for lateral load resistance in a universal testing machine.

Table 2 shows how toe- and end-nailed joints between plates and studs deformed under lateral loads. Joints with COM-PLY studs were more rigid than those with spruce studs. Under the allowable design load of 160 pounds, adjusted deformation of COM-PLY toe-nailed joints was 0.003 inch and that of COM-PLY end-nailed joints was 0.002 inch. According to the Performance Standards for COM-PLY studs, adjusted deformation of toe-nailed joints should be less than 0.010 inch and that of end-nailed joints should be less than 0.005 inch. In comparison, adjusted deformation of toe-nailed spruce joints was 0.007 inch and that of end-nailed spruce joints was 0.006 inch. Again, the standard deviation was smaller for COM-PLY studs than for spruce studs, indicating that COM-PLY studs had more consistent amounts of deformation than spruce studs.

Table 1.--Loads resulting from lateral load test of stud-to-plate joints with COM-PLY and spruce studs

Stud type	Nailing method	Average ultimate load	Standard deviation	Adjusted load
		----------Pounds----------		
COM-PLY	toe	953	140	331
Spruce	toe	727	173	166
COM-PLY	end	501	54	199
Spruce	end	578	116	161

Table 2.--Deformation resulting from lateral load test of stud-to-plate joints with COM-PLY and spruce studs

Stud type	Nailing method	Average deformation at 160-lb load	Standard deviation	Adjusted deformation at 160-lb load
		----------Inch----------		
COM-PLY	toe	0.002	0.001	0.003
Spruce	toe	.005	.003	.007
COM-PLY	end	.001	.001	.002
Spruce	end	.004	.004	.006

Figures 7 and 8 show the load-deformation curves for tests on toe-nailed and end-nailed joints. As shown in figure 7, end-nailed joints with COM-PLY studs reached their proportional limit at about 340 pounds (deformed 0.010 inch), and similar joints with spruce studs reached their proportional limit at about 190 pounds (deformed 0.005 inch). In supporting the allowable design load of 160 pounds, the joints with spruce studs would already have acquired some permanent set that they would not lose when the load is removed. However, end-nailed joints with COM-PLY studs were essentially elastic at the design load of 160 pounds, and as a rule, such joints should have no permanent set when the load is removed.

Toe-nailed joints, however, did not have a well-defined proportional limit, as shown in figure 8. The toe-nailed joints with both spruce and COM-PLY studs were essentially elastic for deformations as large as 0.015 inch and for loads as large as 380 pounds.

The results of these lateral load tests are probably conservative because no supports held the plate portion of the test specimen in a vertical position during the test. It is common practice to rigidly support the plate portion of the test specimen so that it will not rotate during loading. Higher ultimate loads and smaller joint deformations for a given applied load might be possible with such a test arrangement.

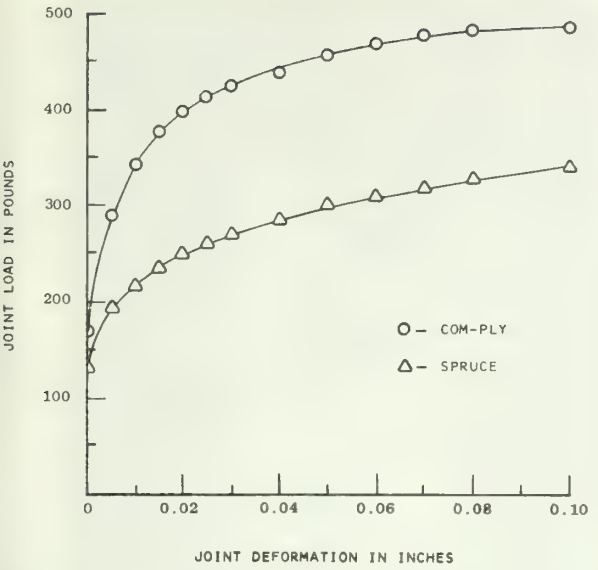

Figure 7.--Load-deformation curves for lateral loads on end-nailed joints between COM-PLY or spruce studs and plates.

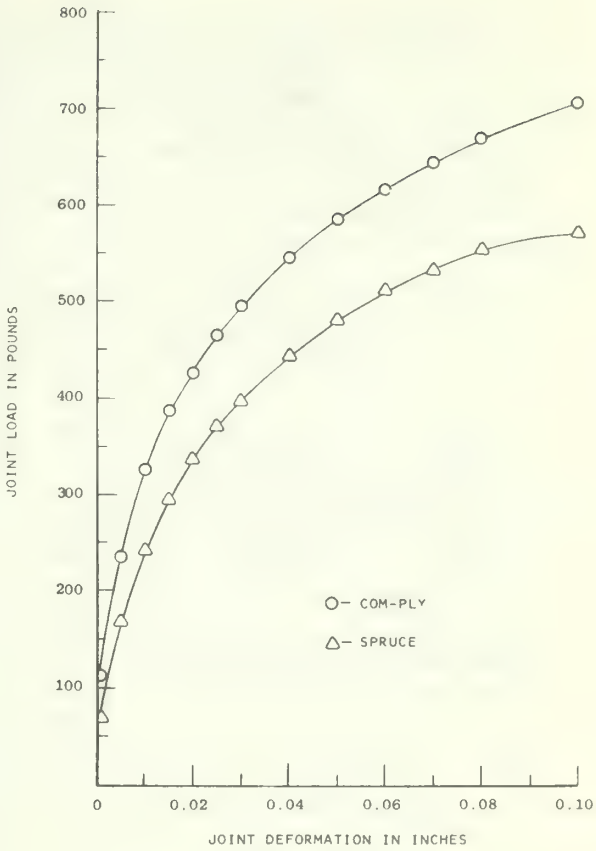

Figure 8.--Load-deformation curves for lateral loads on toe-nailed joints between COM-PLY or spruce studs and plates. →

WITHDRAWAL LOAD ON JOINTS BETWEEN WALL PLATE AND END OF STUD

METHODS

This test method evaluated the uplift load resistance of joints between studs and plates in order to simulate wind loading that uplifts roofs and walls. Scientists tested the specimens dry and after water soaking them for 24 hours and then redrying them. They performed the soak and redry test to investigate the possible loosening of nails because of swelling and shrinking of the particleboard core.

Loading of the test specimens is shown in figure 9. This specimen resembled the specimens tested for lateral load except that the COM-PLY stud section was only 8 inches long. Researchers toe-nailed and end-nailed the specimens for this test as they did those for the lateral load test.

The specimens were placed in a universal testing machine that applied tensile load to the joint until ultimate load occurred (fig. 10). The loading rate was 0.1 inch per minute. Ultimate load was recorded for all specimens.

Researchers tested specimens in their original dry condition as well as those that had been soaked in water at room temperature for 24 hours and then reconditioned to their original dry state.

RESULTS

Table 3 presents the results of testing direct withdrawal of wall plates from the end of toe-nailed and end-nailed joints. These data are for joints fabricated with COM-PLY and spruce studs tested dry.

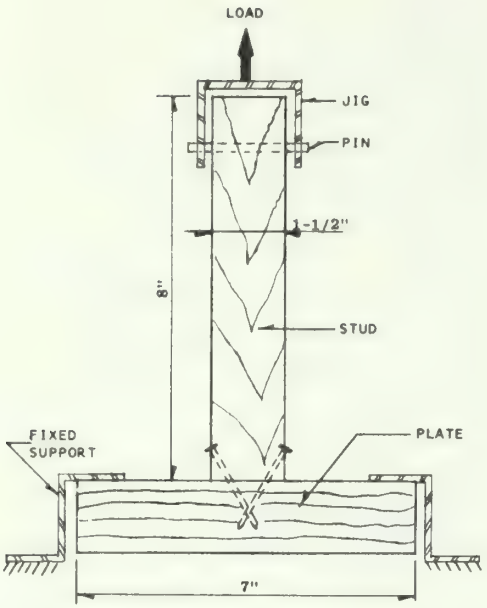

Figure 9.--Withdrawal loading of test specimen of a stud-to-plate joint.

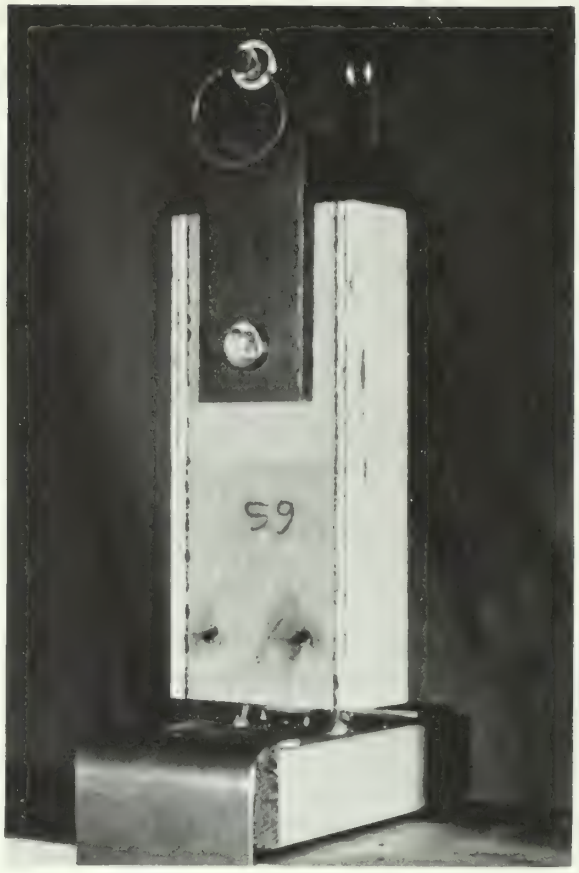

Figure 10.--Specimen being tested for withdrawal load in a universal testing machine.

Table 3.--Loads resulting from direct withdrawal test of dry stud-to-plate joints with COM-PLY and spruce studs

Stud type	Nailing method	Average ultimate load	Standard deviation	Adjusted design load
		---------Pounds----------		
COM-PLY	toe	414	38	173
Spruce	toe	385	92	88
COM-PLY	end	402	62	136
Spruce	end	269	35	99

The design load for spruce loaded in withdrawal, according to specifications issued by the National Forest Products Association (1973, table 16, p. VIII-2), is 21 pounds per inch of penetration for 8d common nails. About 1-1/4 inches of each toe nail penetrates the wall plate; thus, with four nails, the load is 105 pounds. This 105 pounds must be reduced to two-thirds this value to account for toe nailing. Therefore, the typical design withdrawal load per toe-nailed spruce joint would be 70 pounds for normal duration of loading. The Forest Products Association does not provide design values for nailed joints when the nails are driven into the end grain of the wood.

The adjusted loads for spruce toe- and end-nailed joints in this study are reasonably close to typical allowable design values used by designers for many years (table 3). However, joints with COM-PLY studs had considerably higher adjusted withdrawal strengths than those with spruce studs. For toe nailing, the joints with COM-PLY studs had an adjusted load almost twice that of joints with spruce studs, and for end nailing, the joints with COM-PLY studs had an adjusted load about one-third greater than that of their spruce counterparts. Although adjusted design loads for nails driven into the end grain of wood were computed for this study, it is important to emphasize that the industry discourages such designs.

Table 4 presents the results of testing direct withdrawal of wall plates from the ends of toe-nailed and end-nailed joints that had been immersed in tapwater at room temperature and then redried prior to testing. The moisture content of the wood in the joints was approximately 11 percent before immersion and also after redrying. The toe-nailed joints in this group had higher ultimate and adjusted loads than corresponding joints not soaked and redried, whereas end-nailed joints in this group had lower ultimate and adjusted loads than corresponding joints not water soaked and redried. COM-PLY toe-nailed joints had a slightly lower (11 pounds) adjusted load than spruce toe-nailed joints. The 196-pound adjusted load for COM-PLY studs in this test was the only instance in the entire series of tests in which the COM-PLY adjusted loads were lower than the corresponding loads for spruce joints. Nevertheless, the toe-nailed joints with both COM-PLY and spruce studs had adjusted withdrawal strengths well above the typical design values allowed by building codes.

Table 4.--Loads resulting from direct withdrawal test of stud-to-plate joints with COM-PLY and spruce studs after soaking and redrying

Stud type	Nailing method	Average ultimate load	Standard deviation	Adjusted load
		---------Pounds---------		
COM-PLY	toe	466	42	196
Spruce	toe	539	64	207
COM-PLY	end	274	51	82
Spruce	end	216	44	58

As previously noted, withdrawal strength was lower for both COM-PLY and spruce nd-nailed joints that had been water soaked and redried than for corresponding oints tested dry. Codes and specifications usually do not allow design loads for oints with nails loaded in withdrawal from the end grain of the wood. But builders ypically end-nail studs in house frames. Such end-nailed joints help the wall re-st uplift forces created by wind loads. Although spruce studs are used for house raming, end-nailed joints with spruce studs have low, unpredictable strength values or nail withdrawal resistance. The adjusted withdrawal loads of end-nailed joints ith COM-PLY studs were higher than those for corresponding joints with spruce studs. Thus, COM-PLY studs would give at least as much, and probably more, resistance to nail withdrawal as would one of the weaker woods currently used in house framing.

LATERAL LOAD ON JOINTS BETWEEN WALL FACING AND VENEER FACE OF STUD

METHODS

Researchers used this test method to evaluate the lateral resistance of plywood sheathing nailed to the edges of studs. Such joints provide racking resistance to wind or earthquake loads acting on walls.

Researchers cut 1-1/2-inch by 12-inch plywood strips from 3/8-inch-thick, CD-grade, three-ply softwood plywood with the face grain in the long dimension. They cut 12-inch-long, clear sections from COM-PLY and spruce studs. Then one 6d common nail was driven through the plywood at midwidth of the strip and into the stud at midwidth of the stud. The nail was located 2 inches from one end of the stud and 2 inches from one end of the plywood strip (fig. 11).

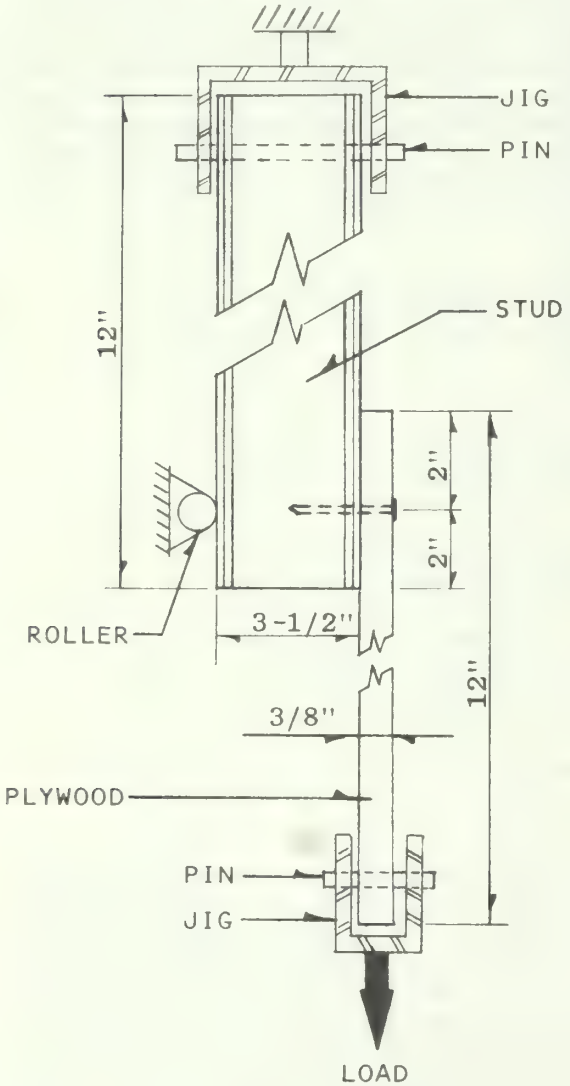

Figure 11.--Test specimen with lateral load on nail driven through a plywood strip and into the veneer face of the stud.

Researchers placed the test specimens in a jig of a universal testing machine (fig. 12) and loaded them in tension at 0.1 inch per minute until ultimate load occurred. A roller support at one end of the stud section prevented lateral movement of the specimen under load. Ultimate load was recorded for each specimen.

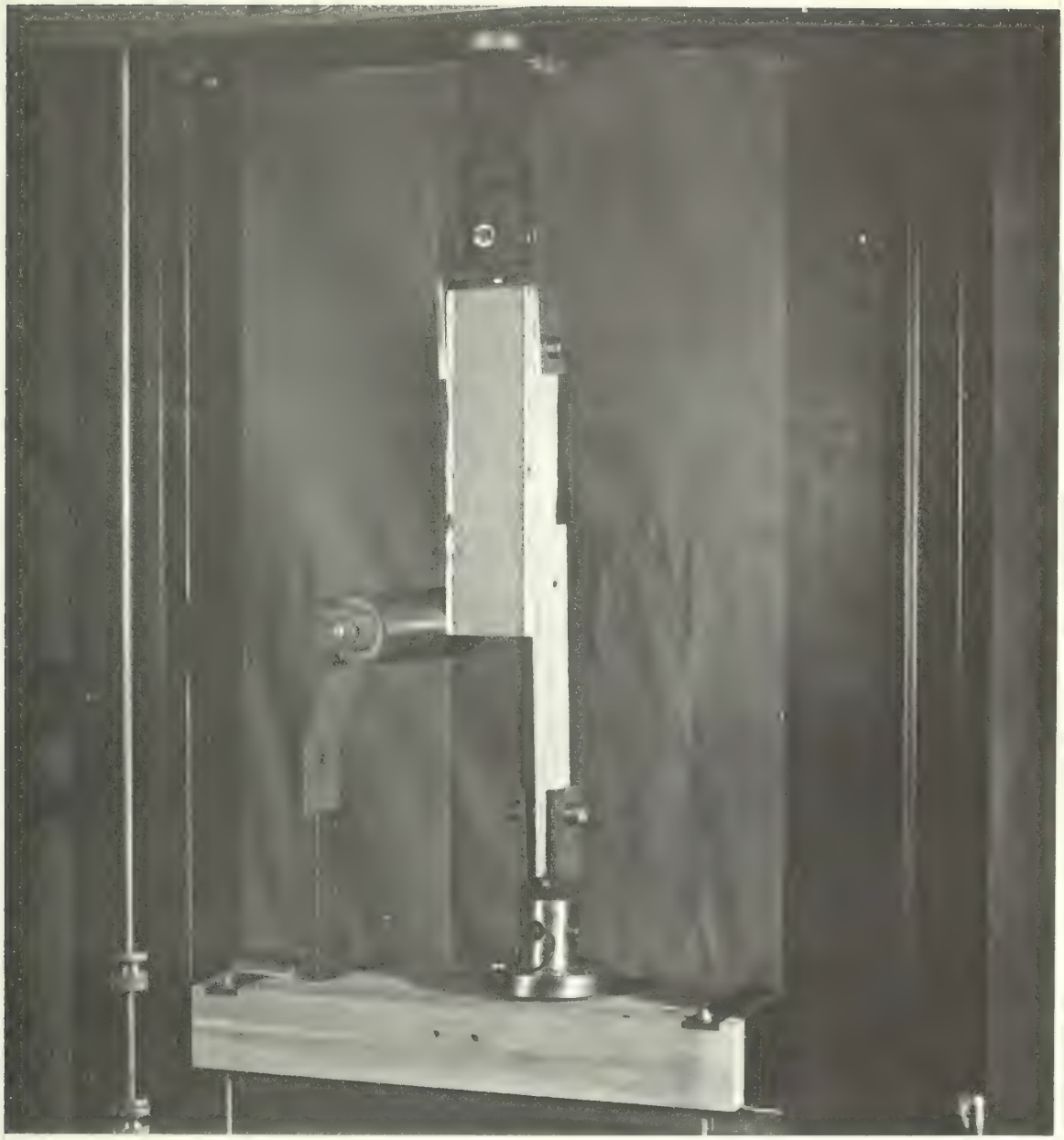

Figure 12.--Specimen being tested for lateral load on nail driven through a plywood strip and into the veneer face of the stud.

RESULTS

Table 5 provides results of testing joints with lateral load on nails driven through 3/8-inch-thick plywood and into the 1-1/2-inch-wide face of the studs. The ultimate and adjusted loads for plywood-to-stud joints were greater with COM-PLY studs than with spruce studs. Specifications issued by the National Forest Products Association (1973, table 17, p. VIII-3) set the allowable lateral design load for this type of joint at 51 pounds when spruce studs are used. Thus, both types of studs in this test exceeded the minimum requirements.

Table 5.--Loads resulting from lateral load test of plywood-to-stud joints with COM-PLY and spruce studs

Stud type	Average ultimate load	Standard deviation	Adjusted load
	----------Pounds----------		
COM-PLY	237	29	89
Spruce	201	31	67

According to specifications issued by the National Forest Products Association (1973), Group I woods such as ash, beech, maple, and oak have the highest lateral load strengths of any wood group. The allowable design load for Group I woods is 78 pounds for the kind of joint used in this test. However, the adjusted lateral load for joints between COM-PLY studs and 3/8-inch plywood sheathing fastened with 6d common nails is 89 pounds (table 5). Thus, the lateral load strength of joints between plywood sheathing and COM-PLY studs compares favorably with that of Group I woods.

Kuenzi (1955) and Wilkinson (1972) showed that lateral loads on nails joining a wood member to another wood or nonwood member induce the greatest bearing stress on the wood at the interface of the joint. Therefore, the lateral load capacity of nails driven into the narrow face of COM-PLY studs should be essentially the same as the lateral load strength of a solid wood stud of the same species as the veneer on the COM-PLY stud. In the present study, this finding was confirmed by the greater lateral loads sustained by the southern pine veneer of the COM-PLY studs than by the spruce studs.

DIRECT NAIL WITHDRAWAL FROM FACE OF STUD

METHODS

This test method measured the direct withdrawal resistance of nails driven into the narrow face of a stud. Although codes and specifications discourage builders from using structural designs that load nails in direct withdrawal from the side grain of lumber, carpenters sometimes use temporary fastenings that stress face nails in direct withdrawal. It is therefore important to determine whether COM-PLY studs can be relied upon to provide as much temporary joint strength as do conventional studs.

Researchers randomly selected 12-inch-long sections of 2 x 4 COM-PLY and spruce studs for this test. One 8d common nail, one 1-1/4-inch drywall nail with annular threads, and one 16d box nail were driven into the narrow edge of each stud section. These nails were driven 4 inches apart to avoid splitting the stud. To simulate fastening 1/2-inch-thick sheathing or drywall material, researchers drove 8d common nails and 1-1/4-inch drywall nails into the stud until only 1/2 inch of the nail shank remained exposed. To simulate fastening nominal 2-inch framing material, they drove the 16d box nails into the stud so that 1-1/2 inches of shank were exposed.

Loading of a specimen to test withdrawal resistance is shown in figure 13. Researchers placed the test specimens in a jig in a universal testing machine (fig. 14) and applied a tensile load to each nail individually at 0.1 inch per minute until ultimate load occurred. Ultimate load of each nailed joint was recorded separately.

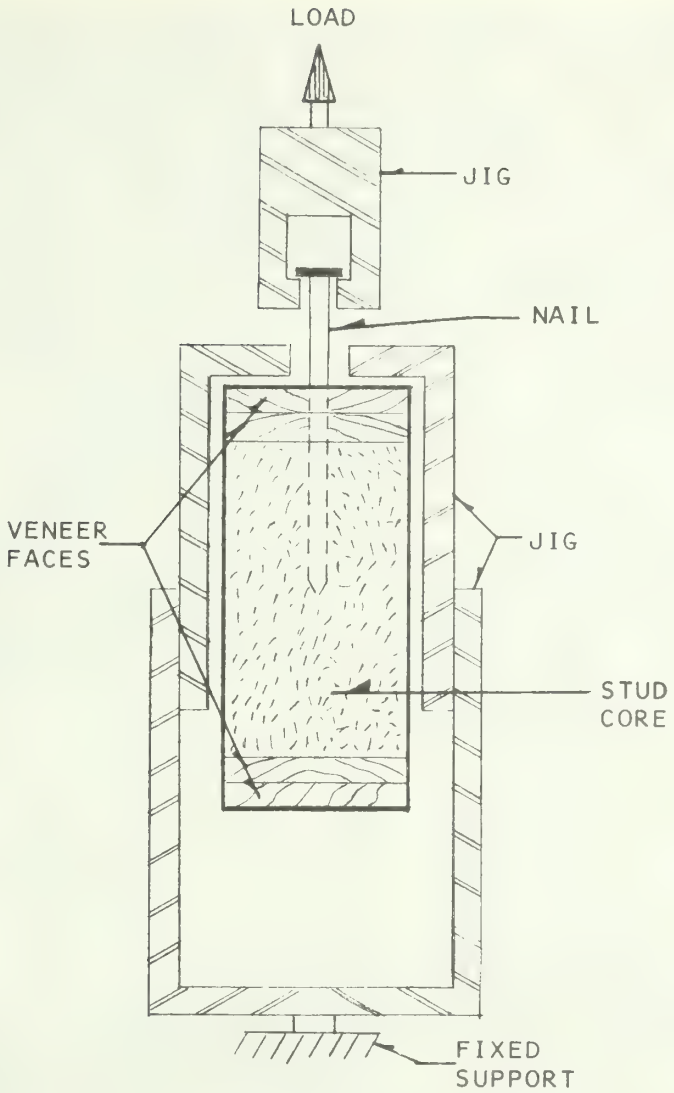

Figure 13.--End cross section of specimen for testing resistance to direct nail withdrawal.

RESULTS

Table 6 presents the results of testing direct withdrawal resistance of nails pulled from the 1-1/2-inch face of COM-PLY and spruce studs. For the three types of nails tested, withdrawal resistance was greater from the narrow face of COM-PLY studs than from that of spruce studs. This difference was significant at the 5 percent level for 16d common nails.

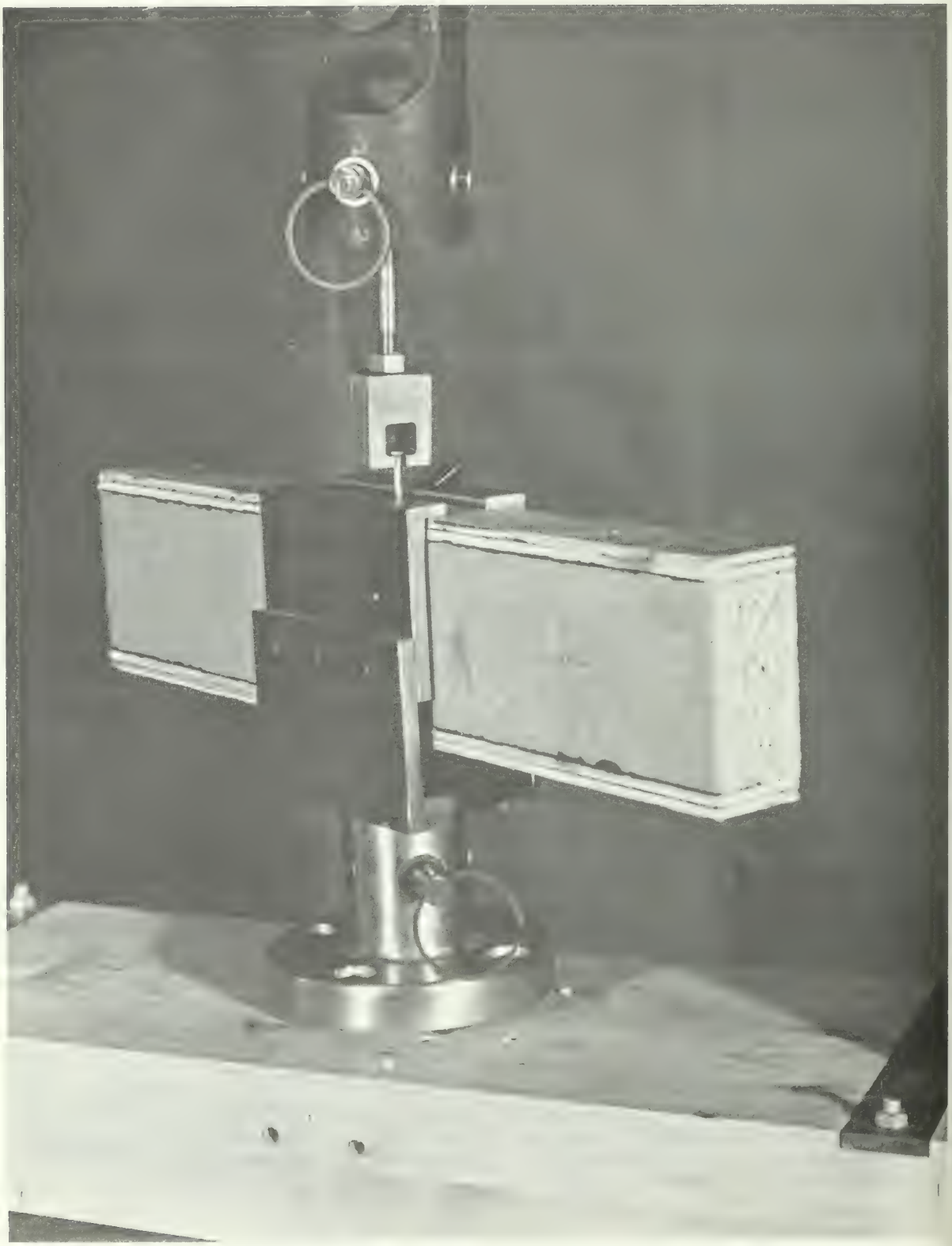

Figure 14.--Specimen being tested for resistance to nail withdrawal in a universal testing machine.

Table 6.--Loads resulting from testing direct withdrawal of nails fastened to the narrow faces of COM-PLY and spruce studs

Stud type	Nail type	Average ultimate load	Standard deviation	Adjusted load
		----------Pounds----------		
COM-PLY	drywall	164	34	44
Spruce	drywall	110	16	39
COM-PLY	8d common	312	39	117
Spruce	8d common	249	65	49
COM-PLY	16d common	271	19	122
Spruce	16d common	221	32	77

CONCLUSIONS AND RECOMMENDATIONS

Nailed joints with COM-PLY studs met the Performance Standard for strength and generally proved stronger and more rigid than those with spruce studs. Therefore, nailed joints between wall plates or wall sheathing and COM-PLY studs fabricated to the specifications described here will be sufficiently strong and rigid to use in framing walls of houses. About the same number and size of splits occurred around nails during fabrication of joints with COM-PLY studs as during fabrication of joints with spruce studs.

Strength of face-nailed joints with COM-PLY studs will probably be about the same as that of joints with solid studs of the same species as the veneer on the COM-PLY stud. Thus, COM-PLY studs made with any veneer species currently accepted and used as solid studs should be acceptable for face-nailed joints without undergoing performance tests.

Strength and rigidity of toe-nailed and especially end-nailed joints with COM-PLY studs will depend on the properties of the particleboard core. Particleboard properties most likely to affect performance of nailed joints are density, internal bond, particle geometry, and amount and type of resin binder. Further evaluation of the effect of these properties on performance of end-nailed joints is desirable.

Because the evaluation of water-soaked and redried joints was limited in this study, additional research on such joints would be valuable to building code officials and others concerned with the durability and safety of residential construction.

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Strength and rigidity of nailed joints between COM PLY studs and wall plates or wall sheathing were sufficient for use in framing walls of houses, exceeding the minimums currently accepted in conventional construction. In almost every test, such joints were stronger and more rigid than their counterparts with studs of solid spruce. Generally, nailed joints with COM PLY studs varied less in strength than did those with spruce studs.

KEYWORDS: Nailed joint strength, wall-framing joints, nailed joint rigidity, toe-nailed joints, end-nailed joints, stud fastening, face nailed joints.

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ields of Veneer and Associated Products from Unthinned, ll-Field Plantations of Slash Pine in the North Florida and South Georgia Flatwoods

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UNIVERSITY OF FLORIDA
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Southeastern Forest Experiment Station

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Yields of Veneer and Associated Products from Unthinned, Old-Field Plantations of Slash Pine in the North Florida and South Georgia Flatwoods

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Abstract.--Mixed yields of veneer, pulpwood, studs (from veneer cores), and chips are predicted for unthinned, old-field plantations of slash pine in the south Georgia and north Florida flatwoods. Stand area, stand age, an estimate of site index, and the present number of trees per acre are required to make predictions. The yield model used here allows specification of the minimum scaling diameter (inside bark) for peeler blocks, the top diameter (outside bark) merchantability limit, the average stump height, the average trim allowed when cutting peeler blocks, and the minimum number of blocks (usually equal to 1) for a tree to be considered merchantable for veneer. However, only a single set of utilization standards are used in the yield table presented. Pulpwood volume comes from veneer-tree topwood and from merchantable--5 inches or larger at breast height--nonveneer trees. Since all yields are broken down by diameter classes, quality assessment is possible.

Keywords: Diameter distributions, taper curves, multiple products.

Veneer has become a major product from our southern pine forest, and forest owners need an easy way of predicting veneer yields per acre from a stand, given its age, average number of stems per acre, and an estimate of site index. This Paper contains estimates of yield per acre in veneer blocks and pulpwood bolts, by breast-high diameter class, for unthinned slash pine stands in north Florida and south Georgia. The pulpwood portion of the stand volume comes from veneer-tree topwood and from merchantable trees (5 inches or more) too small to yield veneer blocks. It is assumed that two studs will be cut from each veneer core. The relative proportions of veneer and pulpwood volumes depend on age, density, and site index, as well as the product utilization standards, which in the model presented can be altered to fit specific practices.

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This Paper is divided into two parts. The first part contains the yield table and information about its preparation. The second part contains details on development of the model.

PART I--APPLICATION

USING THE YIELD TABLE

Table 1 presents veneer and pulpwood yield estimates for ranges in density, site index, and stand age for a representative set of utilization standards. The utilization standards are: (1) a 7.95-inch minimum scaling diameter inside bark (i.b.) for peeler blocks, (2) an 8.5-foot length for peeler blocks, (3) a minimum of 1 peeler block to qualify a tree for veneer, (4) a peeler block trim allowance of 0.15 feet, (5) a top diameter outside bark (o.b.) merchantability limit of 3.95 inches, (6) a 5.25-foot pulpwood bolt length, and (7) an average stump height of 0.5 feet.

As an example, consider a 12-acre, 26-year-old stand estimated to have approximately 300 trees per acre and an average site index of 70. From table 1, we predict this stand's yield as 2,340 peeler blocks with a combined volume of 2,484 cubic feet of grade D or better veneer; 4,680 2 by 4 studs (two from each peeler core); 4,654 cubic feet of wood for chipping (waste from the veneer process); and 396 cords of pulpwood (assuming 90 cubic feet of outside-bark volume per cord). Other information, such as bark volume and numbers of peeler blocks by scaling diameter classes, can also be obtained from the yield table. Furthermore, all the volume estimates are broken down by diameter class.

Users will probably be very interested in seeing how product mix and total volume change with density, site index, and age. They might, for example, want to know how much more veneer would be obtained by holding a stand for, say, 4 more years assuming minimal mortality of merchantable stems. Such values can easily be estimated by consulting the yield table and substracting.

THE YIELD MODEL

The results from four studies of slash pine in Florida and Georgia were used in the construction of the yield prediction model. Clutter and Shephard (1968) developed a stand table prediction model from diameter distribution data on 478 plots in the coastal plain of Georgia and north Florida. We used their model to predict the numbers of trees and mean heights by diameter class. Bennett and Swindel (1972) measured upper-stem diameters of 136 slash pine trees in plantations throughout the middle coastal plain of Georgia and Duval County in northeast Florida. From these data, they developed an equation for estimating stem diameter at any height above the ground, given breast-high diameter and total height. We altered Bennett and Swindel's (1972) taper model to cover a wider range of tree shapes and to fit it to separate sets of inside- and outside-bark diameter measurements from 288 trees (including the original 136 trees just mentioned). Bennett and others (1974) used observed volumes and block scaling diameters of 245 peeler blocks from 39 nonturpentined slash pine trees from natural stands near Waycross, Georgia, to develop a prediction equation for gross cubic-foot volumes of grade D or better veneer. We used their equation as it was published.

A geometric representation of the average stem for a diameter class was obtained by revolving around the height axis one-half the taper curve for the midpoint of the diameter class and the corresponding average total height. Veneer and pulpwood volumes for this mathematically specified average stem were estimated from stem sections defined by product utilization standards. The utilization standards that can be altered in this model are the minimum scaling diameter (i.b. in inches) for peeler blocks, the trim allowance for each peeler block (in feet), the minimum number of peeler blocks for a tree to be called merchantable for veneer, the minimum top diameter (o.b.) for pulpwood (in inches), the length of a pulpwood bolt (in feet), and the average stump height (in feet). Yields using variations of these parameters are not given here, but a general-purpose computer program with a user's guide is being prepared for publication. Nonetheless, table 1 is useful for a large number of cases.

Veneer volume was estimated by predicting the peeler block scaling diameter with the inside-bark taper curve and then applying Bennett and others' (1974) equation. It was assumed that two studs with a combined volume of 0.8262 cubic feet (2 x 0.1458 x 0.3333 x 8.5) would be cut from each peeler core. Chip volume equaled the total inside-bark volume of the veneer section (including trim) minus the veneer and stud volumes. Bark volume was estimated as the volume difference between the inside- and outside-bark stem forms. All volumes from the average stem were multiplied by the diameter-class frequency and summed over all classes to estimate yield per acre.

The performance of our taper-curve approach to computing volumes was checked by comparing our total cubic-foot yield estimates with Bennett's (1970) estimates obtained by conventional methods. The table below shows the deviations of our predictions from Bennett's over the range of stand conditions covered in this work. Eighty-four percent of the differences were less than 5 percent, and the largest difference was less than 7 percent. The advantage of the taper-curve approach is that yields can be estimated for any number of product mixtures for which utilization standards are specified.

Percentage deviations of our predictions of cubic-foot volumes to a 4-inch top by the taper-curve method from Bennett's (1970) predictions by conventional methods

Site index	Number of trees per acre	Age							
		16	18	20	22	24	26	28	30
60	200						1.3	-0.2	0.1
	300						0.6	-0.7	-1.0
	400						0.5	-1.2	-1.3
	500						-0.7	-2.1	-2.5
70	200			0.5	-0.6	-1.6	-1.6	-1.8	-2.5
	300			0.5	-0.8	-1.7	-2.4	-2.6	-3.3
	400				-1.5	-2.5	-2.8	-3.6	-3.8
	500					-3.4	-4.0	-4.7	-4.5
	600						-5.0		
80	200	0.3	-0.3	-1.6	-1.9	-3.3	-3.7	-4.0	-3.3
	300	-0.3	-1.9	-2.3	-3.7	-4.2	-4.6	-4.7	-4.9
	400		-2.5	-3.4	-4.5	-4.8	-5.3	-5.7	-6.2
	500		3.6	-4.1	-4.8	-5.6	-6.2	-6.2	-6.3
	600			-5.3	-6.1	-6.3	-6.8		

Table 1.—Yields of veneer and associated products from unthinned slash pine plantations

AGE: 26 SITE INDEX: 60 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 200

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3												
4	1	40.8	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
5	5	45.7	0	0.0	0	0.0	0.0	0.0	10	5.50	2.95	8.45
6	12	49.4	0	0.0	0	0.0	0.0	0.0	48	31.05	14.00	45.06
7	23	52.2	0	0.0	0	0.0	0.0	0.0	138	97.62	40.69	138.32
8	33	54.3	0	0.0	0	0.0	0.0	0.0	231	202.37	79.67	282.05
9	40	56.1	0	0.0	0	0.0	0.0	0.0	280	332.18	124.83	457.01
10	41	57.6	82	33.88	41	28.55	80.87	59.17	246	298.77	100.55	399.32
11	32	58.8	128	52.89	64	62.58	128.48	89.58	160	190.45	62.15	252.60
12	14	59.8	56	23.14	28	44.33	61.28	46.05	70	104.88	33.17	138.04
13												
14												
15												
TOTALS	201	———	266	109.91	133	135.47	270.63	194.80	1183	1262.83	458.02	1720.85

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
73	46	14	0	0	0	0	0

continued

Table 1.— Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 28 SITE INDEX: 60 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 200

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3												
4	1	42.0	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
5	4	47.1	0	0.0	0	0.0	0.0	0.0	8	4.46	2.39	6.85
6	11	50.9	0	0.0	0	0.0	0.0	0.0	55	29.13	13.06	42.20
7	21	53.7	0	0.0	0	0.0	0.0	0.0	126	91.48	37.93	129.40
8	31	56.0	0	0.0	0	0.0	0.0	0.0	217	195.27	76.51	271.78
9	38	57.8	0	0.0	0	0.0	0.0	0.0	304	324.33	121.34	445.67
10	40	59.3	80	33.06	40	28.15	78.70	57.81	280	303.45	101.72	405.17
11	34	60.6	136	56.19	68	67.73	136.17	95.56	170	214.47	69.54	284.01
12	18	61.6	72	29.75	36	57.87	78.48	59.45	108	142.80	44.90	187.69
13	1	62.5	6	2.48	3	5.74	6.68	4.97	4	5.80	1.85	7.64
14												
15												
TOTALS	199	———	294	121.48	147	159.49	300.03	217.78	1272	1311.18	469.23	1780.41

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
74	53	19	1	0	0	0	0

continued

Table 1.—Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 30 SITE INDEX: 60 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 200

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3												
4	1	43.1	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
5	4	48.4	0	0.0	0	0.0	0.0	0.0	8	4.53	2.42	6.94
6	11	52.2	0	0.0	0	0.0	0.0	0.0	55	29.75	13.28	43.03
7	20	55.2	0	0.0	0	0.0	0.0	0.0	120	89.12	36.78	125.91
8	29	57.5	0	0.0	0	0.0	0.0	0.0	203	187.01	72.97	259.98
9	37	59.3	0	0.0	0	0.0	0.0	0.0	296	323.39	120.52	443.91
10	40	60.9	80	33.06	40	28.40	78.55	57.87	280	314.19	104.97	419.14
11	35	62.2	140	57.85	70	70.78	139.88	98.71	210	231.99	74.84	306.83
12	21	63.3	84	34.71	42	68.37	91.25	69.60	126	174.94	54.74	229.68
13	3	64.2	18	7.44	9	17.56	19.97	14.98	15	18.67	5.89	24.56
14												
15												
TOTALS	201	———	322	133.05	161	185.11	329.64	241.16	1313	1373.57	486.41	1859.98

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
75	59	24	3	0	0	0	0

continued

Table 1.—Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 26 SITE INDEX: 60 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 300

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3												
4	5	41.7	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
5	16	46.8	0	0.0	0	0.0	0.0	0.0	32	17.80	9.54	27.34
6	32	50.5	0	0.0	0	0.0	0.0	0.0	128	84.27	37.84	122.11
7	49	53.3	0	0.0	0	0.0	0.0	0.0	294	212.04	88.04	300.08
8	61	55.6	0	0.0	0	0.0	0.0	0.0	427	381.65	149.72	531.37
9	63	57.4	0	0.0	0	0.0	0.0	0.0	504	533.91	199.97	733.88
10	50	58.9	100	41.32	50	35.10	98.44	72.23	300	375.49	126.00	501.49
11	22	60.1	88	36.36	44	43.62	88.17	61.77	110	136.72	44.40	181.13
12	1	61.2	4	1.65	2	3.20	4.36	3.30	6	7.82	2.46	10.28
13												
14												
15												
TOTALS	299	-----	192	79.33	96	81.92	190.97	137.30	1801	1749.70	657.97	2407.66

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
72	23	1	0	0	0	0	0

continued

Table 1.—Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 28 SITE INDEX: 60 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 300

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3												
4	4	43.0	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
5	15	48.2	0	0.0	0	0.0	0.0	0.0	30	16.92	9.04	25.96
6	30	52.0	0	0.0	0	0.0	0.0	0.0	150	80.92	36.14	117.06
7	46	55.0	0	0.0	0	0.0	0.0	0.0	276	204.37	84.40	288.77
8	59	57.3	0	0.0	0	0.0	0.0	0.0	413	379.19	148.04	527.23
9	62	59.1	0	0.0	0	0.0	0.0	0.0	496	540.14	201.42	741.56
10	52	60.6	104	42.97	52	36.88	102.14	75.22	364	406.42	135.95	542.26
11	28	61.9	112	46.28	56	56.51	111.94	78.93	168	184.30	59.49	243.79
12	2	63.0	8	3.31	4	6.50	8.69	6.63	12	16.55	5.18	21.73
13												
14												
15												
TOTALS	298	———	224	92.56	112	99.88	222.77	160.77	1909	1828.80	679.56	2508.36

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
80	30	2	0	0	0	0	0

continued

Table 1.—Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 30 SITE INDEX: 60 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 300

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D. B. H. CLASS	TREES	MEAN TREE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3												
4	4	44.1	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
5	14	49.5	0	0.0	0	0.0	0.0	0.0	28	15.98	8.52	24.51
6	28	53.4	0	0.0	0	0.0	0.0	0.0	140	77.07	34.26	111.33
7	44	56.4	0	0.0	0	0.0	0.0	0.0	264	139.99	82.22	282.21
8	57	58.8	0	0.0	0	0.0	0.0	0.0	399	375.05	145.82	520.87
9	61	60.7	0	0.0	0	0.0	0.0	0.0	488	544.22	202.17	746.39
10	54	62.2	108	44.62	54	38.63	105.86	78.20	378	436.76	145.51	582.27
11	32	63.6	128	52.89	64	65.53	127.66	90.51	192	221.09	71.01	292.09
12	5	64.7	30	12.40	15	19.92	30.95	21.55	25	26.51	8.60	35.11
13												
14												
15												
TOTALS	299	-----	266	109.91	133	124.08	264.46	190.26	1914	1896.68	698.10	2594.79

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
91	37	5	0	0	0	0	0

continued

Table 1.—Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 26 SITE INDEX: 60 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 400

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3	2	35.2	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
4	14	42.6	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
5	34	47.8	0	0.0	0	0.0	0.0	0.0	68	38.18	20.42	58.60
6	58	51.6	0	0.0	0	0.0	0.0	0.0	290	155.43	69.51	224.94
7	79	54.5	0	0.0	0	0.0	0.0	0.0	474	348.55	144.14	492.69
8	87	56.8	0	0.0	0	0.0	0.0	0.0	609	555.36	217.09	772.45
9	76	58.7	0	0.0	0	0.0	0.0	0.0	608	657.42	245.43	902.85
10	44	60.2	88	36.36	44	31.12	86.48	63.63	308	340.37	113.88	454.25
11	7	61.5	28	11.57	14	14.06	28.00	19.71	35	45.40	14.68	60.08
12												
13												
14												
15												
TOTALS	401	———	116	47.93	58	45.19	114.48	83.34	2392	2140.72	825.15	2965.87

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
51	7	0	0	0	0	0	0

continued

Table 1.—Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 28 SITE INDEX: 60 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 400

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3	2	36.3	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
4	13	43.9	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
5	32	49.3	0	0.0	0	0.0	0.0	0.0	64	36.51	19.47	55.98
6	55	53.2	0	0.0	0	0.0	0.0	0.0	275	150.98	67.15	218.13
7	75	56.2	0	0.0	0	0.0	0.0	0.0	450	339.75	139.77	479.51
8	85	58.6	0	0.0	0	0.0	0.0	0.0	595	557.39	216.84	774.23
9	77	60.5	0	0.0	0	0.0	0.0	0.0	616	684.62	254.46	939.08
10	50	62.0	100	41.32	50	45.72	98.04	72.39	350	402.43	134.13	536.56
11	11	63.3	44	18.18	22	22.48	43.90	31.10	66	75.48	24.26	99.73
12												
13												
14												
15												
TOTALS	400	———	144	59.50	72	68.20	141.94	103.49	2416	2247.16	856.08	3103.23

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
61	11	0	0	0	0	0	0

continued

Table 1. — Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 30 SITE INDEX: 60 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 400

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3	2	37.2	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
4	12	45.1	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
5	30	50.6	0	0.0	0	0.0	0.0	0.0	60	34.65	18.44	53.09
6	52	54.6	0	0.0	0	0.0	0.0	0.0	260	145.75	64.52	210.26
7	72	57.7	0	0.0	0	0.0	0.0	0.0	432	333.69	136.65	470.34
8	83	60.1	0	0.0	0	0.0	0.0	0.0	581	557.25	215.90	773.15
9	78	62.0	0	0.0	0	0.0	0.0	0.0	624	710.24	262.99	973.22
10	55	63.7	110	45.45	55	39.62	107.64	78.72	385	458.10	152.21	610.31
11	17	65.0	68	28.10	34	35.24	67.70	48.23	102	122.38	39.14	161.52
12												
13												
14												
15												
TOTALS	401	-----	178	73.55	89	74.86	175.34	127.95	2444	2362.05	889.85	3251.90

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
72	17	0	0	0	0	0	0

continued

Table 1.—Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 26 SITE INDEX: 60 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 500

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3	7	36.0	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
4	27	43.6	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
5	57	48.9	0	0.0	0	0.0	0.0	0.0	114	64.77	34.57	99.33
6	88	52.8	0	0.0	0	0.0	0.0	0.0	440	240.05	106.92	346.97
7	107	55.8	0	0.0	0	0.0	0.0	0.0	642	481.51	198.36	679.86
8	105	58.1	0	0.0	0	0.0	0.0	0.0	735	683.88	266.39	950.25
9	78	60.0	0	0.0	0	0.0	0.0	0.0	624	688.60	256.22	944.82
10	30	61.5	60	24.79	30	21.38	58.26	43.42	210	239.06	79.76	318.82
11	1	62.8	4	1.65	2	2.03	3.99	2.82	6	6.77	2.18	8.94
12												
13												
14												
15												
TOTALS	[illegible]	-----	64	26.44	32	23.41	62.25	46.25	2771	2404.62	944.38	3349.00

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
31	1	0	0	0	0	0	0

continued

Table 1.—Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 28 SITE INDEX: 60 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 500

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3	6	37.1	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
4	25	44.9	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
5	53	50.4	0	0.0	0	0.0	0.0	0.0	106	61.18	32.56	93.74
6	83	54.4	0	0.0	0	0.0	0.0	0.0	415	231.87	102.71	334.57
7	103	57.5	0	0.0	0	0.0	0.0	0.0	618	475.75	194.96	670.71
8	105	59.9	0	0.0	0	0.0	0.0	0.0	735	702.56	272.35	974.91
9	83	61.8	0	0.0	0	0.0	0.0	0.0	664	753.18	279.03	1032.21
10	38	63.4	76	31.40	38	27.34	74.39	55.07	266	314.97	104.70	419.67
11	2	64.8	8	3.31	4	4.14	7.97	5.67	12	14.30	4.58	18.88
12												
13												
14												
15												
TOTALS	498	-----	84	34.71	42	31.48	82.36	60.74	2816	2553.81	990.89	3544.69

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
40	2	0	0	0	0	0	0

continued

Table 1.—Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 30 SITE INDEX: 60 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 500

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3	6	38.1	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
4	23	46.1	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
5	50	51.7	0	0.0	0	0.0	0.0	0.0	100	58.46	31.04	89.51
6	79	55.8	0	0.0	0	0.0	0.0	0.0	395	225.34	99.35	324.69
7	100	59.0	0	0.0	0	0.0	0.0	0.0	700	472.74	192.87	665.61
8	105	61.5	0	0.0	0	0.0	0.0	0.0	840	719.34	277.72	997.06
9	86	63.5	0	0.0	0	0.0	0.0	0.0	688	799.40	295.07	1094.46
10	45	65.1	90	37.19	45	32.64	87.92	65.28	315	395.90	127.88	513.78
11	5	66.5	20	8.26	10	10.49	19.88	14.23	30	37.48	11.94	49.42
12												
13												
14												
15												
TOTALS	499	-----	110	45.45	55	43.13	107.80	79.51	3068	2698.67	1035.87	3734.54

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
50	5	0	0	0	0	0	0

continued

Table 1.—Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 20 SITE INDEX: 70 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 200

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3												
4												
5	3	46.6	0	0.0	0	0.0	0.0	0.0	6	3.32	1.78	5.11
6	11	50.3	0	0.0	0	0.0	0.0	0.0	44	28.85	12.97	41.82
7	22	53.1	0	0.0	0	0.0	0.0	0.0	132	94.82	39.40	134.22
8	33	55.3	0	0.0	0	0.0	0.0	0.0	231	205.63	80.72	286.36
9	41	57.1	0	0.0	0	0.0	0.0	0.0	328	346.11	129.72	475.83
10	42	58.6	84	34.71	42	29.43	82.72	60.66	252	313.52	105.27	418.79
11	33	59.8	132	54.54	66	65.25	132.30	92.60	165	203.32	66.09	269.41
12	14	60.9	56	23.14	28	44.74	61.14	46.16	84	109.52	34.20	142.71
13												
14												
15												
TOTALS	199	———	272	112.39	136	139.43	276.15	199.42	1242	1304.09	470.15	1774.25

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
75	47	14	0	0	0	0	0

continued

Table 1.—Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 22 SITE INDEX: 70 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 200

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3												
4												
5	3	48.9	0	0.0	0	0.0	0.0	0.0	5	3.41	1.82	5.23
6	9	52.8	0	0.0	0	0.0	0.0	0.0	45	24.56	10.94	35.50
7	19	55.8	0	0.0	0	0.0	0.0	0.0	114	85.50	35.29	120.79
8	30	58.1	0	0.0	0	0.0	0.0	0.0	210	195.50	76.14	271.64
9	38	60.0	0	0.0	0	0.0	0.0	0.0	304	335.66	124.83	460.54
10	41	61.6	82	33.88	41	23.22	30.44	54.34	287	316.97	121.03	436.06
11	36	62.9	144	59.50	72	78.28	144.74	101.62	216	248.82	73.48	322.29
12	21	64.0	84	34.71	42	64.74	11.11	43.70	126	173.44	55.41	228.85
13	2	64.9	12	4.96	6	11.80	13.29	13.21	12	12.93	4.34	17.27
14												
15												
TOTALS	199	-----	322	133.05	161	183.04	353.58	246.74	1319	1405.90	511.43	1917.33

NUMBER OF VENEER BOLTS BY BOLT DIAMETER (IN.)

8	9	10	11	12	13	14	15
77	54	24	3	3	0	0	0

continued

Table 1. — Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 24 SITE INDEX: 70 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 202

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	STUD	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3												
4												
5	3	51.0	0	0.0	0	0.0	0.0	0.0	6	3.48	1.85	5.33
6	8	55.1	0	0.0	0	0.0	0.0	0.0	40	22.56	9.97	32.53
7	17	58.2	0	0.0	0	0.0	0.0	0.0	102	79.38	32.46	111.84
8	27	60.8	0	0.0	0	0.0	0.0	0.0	216	182.65	70.67	253.33
9	36	62.5	0	0.0	0	0.0	0.0	0.0	288	330.31	122.16	452.48
10	40	64.2	80	33.06	40	28.89	78.23	58.00	280	336.79	111.79	448.58
11	37	65.5	148	61.15	74	77.03	147.25	105.08	222	270.39	86.35	356.74
12	25	66.7	150	61.98	75	101.98	154.37	108.40	125	143.57	46.14	189.71
13	6	67.7	36	14.87	18	36.41	39.64	30.29	30	42.85	13.33	56.18
14												
15												
TOTALS	199	---	414	171.06	207	244.31	419.48	301.76	1309	1411.98	494.75	1906.73

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
102	68	31	6	0	0	0	0

continued

Table 1.— Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 26 SITE INDEX: 70 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 200

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3												
4												
5	2	52.8	0	0.0	0	0.0	0.0	0.0	4	2.36	1.25	3.62
6	8	57.0	0	0.0	0	0.0	0.0	0.0	40	23.21	10.19	33.40
7	16	60.2	0	0.0	0	0.0	0.0	0.0	112	77.04	31.32	108.35
8	25	62.8	0	0.0	0	0.0	0.0	0.0	200	174.56	67.18	241.73
9	34	64.8	0	0.0	0	0.0	0.0	0.0	306	322.18	118.56	440.74
10	39	66.5	73	32.23	39	28.47	76.09	56.63	312	343.61	113.59	457.20
11	37	67.7	148	61.15	74	78.42	146.84	105.56	222	237.87	91.37	329.24
12	28	69.1	168	69.42	84	117.17	172.41	122.24	140	175.66	55.91	231.57
13	11	70.1	66	27.27	33	68.24	72.30	55.91	66	85.64	26.41	112.05
14												
15												
TOTALS	200	-----	460	190.17	230	292.33	467.64	340.34	1402	1492.14	515.77	2007.91

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
104	76	33	11	0	-	0	0

continued

Table 1.— Yield of veneer and associated products from unthinned slash pine plantations (continued)

STAND DESCRIPTION			PRODUCTS FROM VENEER PORTION						RESIDUES FROM MERCHANTABLE PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	TREES	GREEN VOLUME	VENEER BOLTS	NET VENEER VOLUME	CORE VOLUME	SAW LOG VOLUME	VENEER BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3												
4												
5	-	58.4	-	0.0	-	0.0	0.0	0.0	-	0.00	0.00	0.00
6	7	58.3	-	0.0	-	0.0	0.0	0.0	35	23.80	5.89	29.69
7	15	62.1	1	1.0	1	0.9	0.0	0.0	100	73.17	31.20	104.37
8	24	64.7	1	1.1	1	0.9	0.0	0.0	192	172.23	65.97	238.20
9	32	66.8	2	2.0	1	0.9	0.0	0.0	288	311.73	114.23	425.97
10	37	68.5	74	76.58	37	27.25	72.83	168.74	296	339.27	111.64	450.91
11	37	69.9	148	61.15	74	79.57	146.50	105.97	259	333.47	35.85	333.31
12	30	71.2	180	74.17	90	123.17	144.27	131.74	180	232.98	68.33	266.41
13	15	72.2	124	43.59	62	105.07	126.63	41.13	62	74.30	24.01	98.30
14	1	73.2	8	3.31	4	3.82	3.93	7.00	5	5.11	1.91	8.02
15												
TOTALS	209	-----	538	278.94	269	349.86	538.37	389.60	1424	1566.55	517.89	2224.44

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
119	83	45	16	1	0	0	0

continued

Table 1.—Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 30 SITE INDEX: 70 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 220

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TRUE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3												
4												
5	2	65.0	0	0.0	0	0.0	0.0	0.0	4	2.44	1.28	3.72
6	7	60.3	0	0.0	0	0.0	0.0	0.0	35	21.24	9.24	30.48
7	14	63.7	0	0.0	0	0.0	0.0	0.0	88	72.33	28.82	101.15
8	22	66.4	0	0.0	0	0.0	0.0	0.0	176	161.66	61.69	223.35
9	31	68.5	0	0.0	0	0.0	0.0	0.0	279	309.40	111.94	421.34
10	36	70.3	72	29.75	26	26.72	69.96	[illegible]	324	440.87	111.86	[illegible]
11	37	71.8	148	61.19	74	80.53	146.22	[illegible]	259	337.42	93.94	[illegible]
12	31	73.1	186	76.89	93	134.72	140.00	136.82	186	[illegible]	66.20	[illegible]
13	18	74.1	144	[illegible]	72	128.95	151.66	[illegible]	93	[illegible]	31.94	[illegible]
14	2	75.3	16	6.61	8	20.03	17.72	[illegible]	10	[illegible]	3.13	[illegible]
15												
TOTALS	220	-----	566	233.67	283	390.94	575.64	419.63	1425	[illegible]	530.47	[illegible]

NUMBER OF TREES PER 80-FOOT BOLT BY DBH CLASS

8	9	10	11	12	13	14	15
122	88	61	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

continued

Table 1.—Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 20 SITE INDEX: 70 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 300

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3												
4	3	42.4	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
5	14	47.6	0	0.0	0	0.0	0.0	0.0	28	15.70	8.40	24.10
6	31	51.4	0	0.0	0	0.0	0.0	0.0	155	82.84	37.08	119.91
7	49	54.3	0	0.0	0	0.0	0.0	0.0	294	215.40	89.15	304.55
8	63	56.6	0	0.0	0	0.0	0.0	0.0	441	400.52	156.67	557.20
9	65	58.4	0	0.0	0	0.0	0.0	0.0	520	559.97	209.18	769.15
10	52	59.9	104	42.97	52	36.73	102.23	75.18	364	399.87	133.86	533.73
11	23	61.2	92	38.01	46	46.09	92.04	64.73	115	147.92	47.87	195.79
12	1	62.3	4	1.65	2	3.23	4.35	3.31	6	8.09	2.54	10.62
13												
14												
15												
TOTALS	301	-----	200	82.64	100	86.05	198.63	143.22	1923	1830.30	684.75	2515.05

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
75	24	1	0	0	0	0	0

continued

Table 1.—Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 22 SITE INDEX: 70 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 300

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3												
4	3	44.6	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
5	12	50.0	0	0.0	0	0.0	0.0	0.0	24	13.90	7.35	21.15
6	27	54.0	0	0.0	0	0.0	0.0	0.0	135	74.99	33.26	108.26
7	44	57.1	0	0.0	0	0.0	0.0	0.0	264	202.00	82.88	284.88
8	58	59.5	0	0.0	0	0.0	0.0	0.0	406	385.66	149.68	535.33
9	64	61.4	0	0.0	0	0.0	0.0	0.0	512	576.96	213.97	790.92
10	56	63.0	112	46.28	56	40.20	109.68	81.13	392	459.84	152.99	612.83
11	32	64.3	128	52.84	64	65.94	127.54	40.65	192	225.83	72.37	298.20
12	5	65.4	30	12.40	15	20.10	30.92	21.60	25	27.33	8.83	36.17
13												
14												
15												
TOTALS	301	-----	270	111.52	135	126.25	268.14	143.38	1950	1966.41	721.33	2687.74

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
93	37	5	0	0	0	0	0

continued

Table 1.—Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 24 SITE INDEX: 70 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 105

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION					PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	STUMPS	GROSS VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3												
4	2	46.5	0	0.0		0.0	0.0	0.0	3	0.0	0.0	0.0
5	10	52.2	0	0.0	0	0.0	0.0	0.0	20	11.75	6.23	17.98
6	24	56.3	0	0.0	0	0.0	0.0	0.0	123	68.94	30.34	99.27
7	40	59.5	0	0.0	0	0.0	0.0	0.0	280	190.45	77.59	268.04
8	54	62.0	0	0.0	0	0.0	0.0	0.0	432	372.76	143.73	516.49
9	62	64.0	0	0.0	0	0.0	0.0	0.0	446	530.52	214.05	744.58
10	57	65.6	114	47.10	57	41.45	111.31	82.72	399	433.98	168.54	657.52
11	39	67.0	156	64.46	78	82.13	154.93	111.08	238	296.72	94.39	331.09
12	11	68.2	66	27.27	33	45.62	67.80	47.41	55	165.86	21.35	88.21
13												
14												
15												
TOTALS	299	-----	336	138.83	168	169.20	334.04	241.21	2,146	2032.99	791.22	3443.27

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
107	50	11	0	0	0	0	

continued

Table 1.—Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 26 SITE INDEX: 70 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 300

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3												
4	2	48.2	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
5	9	54.0	0	0.0	0	0.0	0.0	0.0	18	10.76	5.69	16.45
6	22	58.3	0	0.0	0	0.0	0.0	0.0	110	64.96	28.42	93.38
7	37	61.6	0	0.0	0	0.0	0.0	0.0	259	181.67	73.57	255.24
8	51	64.2	0	0.0	0	0.0	0.0	0.0	408	363.39	139.36	502.75
9	60	66.3	0	0.0	0	0.0	0.0	0.0	540	580.32	212.89	793.21
10	58	68.0	116	47.93	58	42.62	112.98	84.29	464	525.95	173.43	699.38
11	43	69.4	172	71.07	86	92.13	170.36	123.03	301	347.96	110.03	457.99
12	17	70.6	102	42.15	51	72.25	104.49	74.54	85	112.63	35.63	148.26
13												
14												
15												
TOTALS	299	———	390	161.15	195	206.99	387.83	281.87	2185	2187.64	779.02	2966.66

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
118	60	17	0	0	0	0	0

continued

Table 1.— Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 28 SITE INDEX: 70 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 402

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3												
4	2	49.6	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
5	9	55.7	0	0.0	0	0.0	0.0	0.0	18	10.94	5.77	16.71
6	20	60.1	0	0.0	0	0.0	0.0	0.0	100	60.49	26.32	86.81
7	35	63.5	0	0.0	0	0.0	0.0	0.0	245	176.49	71.11	247.60
8	49	66.1	0	0.0	0	0.0	0.0	0.0	392	358.84	136.99	495.83
9	58	68.3	0	0.0	0	0.0	0.0	0.0	522	576.85	210.74	787.59
10	58	70.0	116	47.93	58	42.98	112.75	84.39	464	546.47	179.59	726.06
11	46	71.5	184	76.03	92	99.95	181.83	132.12	322	392.12	123.41	515.53
12	23	72.8	138	57.02	69	99.72	141.01	101.44	138	163.60	51.36	214.96
13	1	73.9	8	3.31	4	7.14	8.43	6.11	5	5.34	1.71	7.05
14												
15												
TOTALS	301	———	446	184.28	223	249.79	444.02	324.06	2206	2231.13	807.00	3038.14

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
128	70	24	1	0	0	0	0

continued

Table 1.—Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 30 SITE INDEX: 70 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 300

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3												
4	2	50.9	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
5	8	57.1	0	0.0	0	0.0	0.0	0.0	16	9.85	5.19	15.04
6	19	61.7	0	0.0	0	0.0	0.0	0.0	95	58.68	25.42	84.10
7	33	65.2	0	0.0	0	0.0	0.0	0.0	231	170.34	68.34	238.68
8	46	67.9	0	0.0	0	0.0	0.0	0.0	368	344.97	131.19	476.16
9	56	70.1	0	0.0	0	0.0	0.0	0.0	504	570.50	207.67	778.17
10	58	71.9	116	47.93	58	43.28	112.55	84.48	464	564.87	185.13	750.00
11	48	73.4	192	79.33	96	105.53	189.37	138.33	336	427.61	134.04	561.65
12	27	74.7	162	66.94	81	119.00	165.18	119.67	162	203.96	63.62	267.58
13	3	75.8	24	9.92	12	21.89	25.23	18.44	15	17.41	5.53	22.94
14												
15												
TOTALS	300	———	494	204.12	247	289.70	492.34	360.92	2191	2368.19	826.11	3194.31

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
136	78	30	3	0	0	0	0

continued

Table 1.--Yields of veneer and associated products from unthinned [illegible] (continued)

[illegible] NUMBER OF SURVIVING TREES, 401

D.B.H. CLASS	STAND STRUCTURE: TREES	STAND STRUCTURE: MEAN TREE HEIGHT	PRODUCTS FROM VENEER PORTION: STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PRODUCTS FROM PULPWOOD PORTION: PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3	1	37.7	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
4	9	45.6	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
5	27	51.2	0	0.0	0	0.0	0.0	0.0	54	31.42	16.70	48.11
6	51	55.2	0	0.0	0	0.0	0.0	0.0	255	144.24	63.72	207.96
7	73	58.3	0	0.0	0	0.0	0.0	0.0	511	341.73	139.67	481.40
8	85	60.8	0	0.0	0	0.0	0.0	0.0	680	576.71	223.04	799.75
9	81	62.8	0	0.0	0	0.0	0.0	0.0	648	745.42	275.56	1020.98
10	56	64.4	112	46.28	56	40.49	109.50	81.21	392	473.49	157.11	630.60
11	18	65.7	72	29.75	36	37.54	71.62	51.14	108	132.31	42.23	174.54
12												
13												
14												
15												
TOTALS	401	-----	184	76.03	92	78.02	181.12	132.35	2648	2445.32	918.03	3363.35

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
74	18	0	0	0	0	0	0

continued

Table 1.—Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 24 SITE INDEX: 70 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 400

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3	1	39.3	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
4	8	47.5	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
5	24	53.3	0	0.0	0	0.0	0.0	0.0	48	28.52	15.10	43.62
6	46	57.6	0	0.0	0	0.0	0.0	0.0	230	134.45	58.95	193.40
7	68	60.8	0	0.0	0	0.0	0.0	0.0	476	330.16	133.99	464.15
8	82	63.4	0	0.0	0	0.0	0.0	0.0	656	577.62	221.96	799.58
9	81	65.4	0	0.0	0	0.0	0.0	0.0	729	774.40	284.60	1059.00
10	62	67.1	124	51.24	62	45.39	120.89	80.06	496	553.07	182.63	735.71
11	28	68.5	112	46.29	56	59.62	111.04	79.98	196	221.57	70.21	291.78
12	1	69.7	6	2.48	3	4.21	6.15	4.27	5	6.42	2.04	8.46
13												
14												
15												
TOTALS	401	-----	242	99.99	121	109.22	238.07	174.41	2836	2626.21	969.48	3595.69

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
91	29	1	0	0	0	0	0

continued

Table 1.—Yields of veneer and associated products from untreated slash pine plantations (continued)

AGE: 26 SITE INDEX: 70 (25-YEAR BASIS) NUMBER OF SAMPLING POINTS: 100

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3	1	40.7	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
4	7	49.2	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
5	22	55.2	0	0.0	0	0.0	0.0	0.0	44	26.63	14.06	40.69
6	42	59.6	0	0.0	0	0.0	0.0	0.0	210	126.30	55.03	181.33
7	63	63.0	0	0.0	0	0.0	0.0	0.0	441	315.56	127.31	442.88
8	78	65.6	0	0.0	0	0.0	0.0	0.0	624	567.31	216.84	784.14
9	81	67.8	0	0.0	0	0.0	0.0	0.0	729	799.84	292.51	1092.35
10	67	69.5	134	55.37	67	49.54	130.31	97.46	536	625.07	205.60	830.66
11	36	71.0	144	59.59	72	77.85	142.39	103.30	252	302.83	95.42	398.25
12	4	72.2	24	9.82	12	17.25	24.54	17.61	24	27.94	8.79	36.73
13												
14												
15												
TOTALS	401	-----	302	124.78	151	144.74	297.24	218.37	2860	2791.47	1015.55	3807.03

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
107	40	4	0	0	0	0	0

continued

Table 1.—Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 28 SITE INDEX: 70 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 400

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3	1	41.9	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
4	6	50.7	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
5	20	56.9	0	0.0	0	0.0	0.0	0.0	40	24.58	12.95	37.53
6	39	61.5	0	0.0	0	0.0	0.0	0.0	195	120.13	52.07	172.19
7	60	64.9	0	0.0	0	0.0	0.0	0.0	420	308.66	123.90	432.57
8	75	67.6	0	0.0	0	0.0	0.0	0.0	600	560.53	213.27	773.80
9	80	69.8	0	0.0	0	0.0	0.0	0.0	720	812.19	295.80	1107.99
10	69	71.6	138	57.02	69	51.44	133.93	100.49	552	668.84	219.29	888.13
11	42	73.1	168	69.42	84	92.18	165.75	120.98	294	371.82	116.61	488.42
12	8	74.4	48	19.83	24	35.18	48.96	35.43	48	59.92	18.71	78.63
13												
14												
15												
TOTALS	400	-----	354	146.27	177	178.80	348.64	256.90	2869	2926.66	1052.59	3979.25

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
119	50	8	0	0	0	0	0

continued

Table 1.—Yields of veneer and associated products from unthinned slash pine plantations (continued)

STAND STRUCTURE			PRODUCTS FROM VENEER LOGS						PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	SLDS	SLDS VOLUME	VENEER BOLTS	NET VENEER VOLUME	CORE VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3	1	43.0	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
4	6	52.1	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
5	19	58.4	0	0.0	0	0.0	0.0	0.0	77	28.69	12.45	41.14
6	37	63.1	0	0.0	0	0.0	0.0	0.0	222	116.39	50.22	166.61
7	57	66.6	0	0.0	0	0.0	0.0	0.0	393	300.07	119.94	420.01
8	73	69.4	0	0.0	0	0.0	0.0	0.0	657	568.72	211.76	780.48
9	79	71.7	0	0.0	0	0.0	0.0	0.0	390	821.57	298.15	1119.72
10	71	73.5	142	58.67	71	53.30	137.58	103.50	639	711.11	232.51	943.61
11	47	75.1	188	77.68	90	104.53	185.13	135.83	376	434.68	135.81	570.50
12	12	76.4	72	29.75	36	53.61	73.28	53.41	72	95.33	29.58	124.91
13												
14												
15												
TOTALS	402	———	402	166.10	201	211.24	395.98	292.74	3212	3961.55	1090.41	4151.98

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
130	59	12	0	0	0	0	0

continued

Table 1.— Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 24 SITE INDEX: 70 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 500

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3	3	40.1	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
4	17	48.6	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
5	42	54.5	0	0.0	0	0.0	0.0	0.0	84	50.48	26.68	77.16
6	72	58.9	0	0.0	0	0.0	0.0	0.0	360	214.31	93.59	307.90
7	96	62.2	0	0.0	0	0.0	0.0	0.0	672	475.49	192.25	667.74
8	105	64.8	0	0.0	0	0.0	0.0	0.0	840	754.78	289.05	1043.83
9	93	66.9	0	0.0	0	0.0	0.0	0.0	837	907.54	332.48	1240.03
10	58	68.6	116	47.93	58	42.73	112.90	84.32	464	532.35	175.34	707.70
11	14	70.1	56	23.14	28	30.13	55.43	40.11	98	115.20	36.37	151.57
12												
13												
14												
15												
TOTALS	500	———	172	71.07	86	72.87	168.33	124.43	3355	3050.15	1145.76	4195.92

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
72	14	0	0	0	0	0	0

continued

Table 1.—Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 26 SITE INDEX: 70 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 500

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NPT VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3	3	41.6	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
4	15	50.4	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
5	39	56.5	0	0.0	0	0.0	0.0	0.0	78	47.74	25.16	72.90
6	67	61.0	0	0.0	0	0.0	0.0	0.0	335	205.06	89.01	294.07
7	91	64.4	0	0.0	0	0.0	0.0	0.0	637	464.85	186.84	651.69
8	103	67.1	0	0.0	0	0.0	0.0	0.0	824	764.52	291.23	1055.75
9	95	69.3	0	0.0	0	0.0	0.0	0.0	855	957.57	349.11	1306.68
10	66	71.1	132	54.54	66	49.10	128.17	96.09	528	633.51	207.87	841.39
11	22	72.6	88	36.36	44	48.12	86.87	63.31	154	192.22	60.36	252.58
12												
13												
14												
15												
TOTALS	501	———	220	90.90	110	97.22	215.04	159.40	3411	3265.49	1209.58	4475.05

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
88	22	0	0	0	0	0	0

continued

Table 1.—Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 28 SITE INDEX: 70 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 500

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3	2	42.8	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
4	14	51.9	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
5	36	58.2	0	0.0	0	0.0	0.0	0.0	72	44.75	23.53	68.28
6	62	62.8	0	0.0	0	0.0	0.0	0.0	372	194.38	83.93	278.30
7	87	66.4	0	0.0	0	0.0	0.0	0.0	609	456.45	182.55	639.01
8	100	69.2	0	0.0	0	0.0	0.0	0.0	800	762.94	289.33	1052.28
9	96	71.4	0	0.0	0	0.0	0.0	0.0	960	994.91	361.24	1356.14
10	71	73.2	142	58.67	71	53.25	137.61	103.49	639	707.73	231.51	939.29
11	30	74.8	120	49.58	60	66.49	119.20	86.66	210	275.74	86.20	361.94
12	1	76.1	6	2.48	3	4.46	6.11	4.45	6	7.88	2.45	10.33
13												
14												
15												
TOTALS	499	-----	268	110.74	134	124.19	261.92	194.60	3768	3444.83	1260.73	4705.55

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
102	31	1	0	0	0	0	0

continued

Table 1.—Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 30 SITE INDEX: 70 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 501

STAND STRUCTURE			PRODUCTS FROM VENEER ROTATION						PRODUCTS FROM PULPWOOD ROTATION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	STUMPS	STUMP VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3	2	44.5	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
4	13	53.3	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
5	33	59.7	0	0.0	0	0.0	0.0	0.0	49	41.62	21.83	63.45
6	59	64.5	0	0.0	0	0.0	0.0	0.0	354	188.93	81.29	270.10
7	83	68.1	0	0.0	0	0.0	0.0	0.0	564	445.81	177.54	623.35
8	98	71.0	0	0.0	0	0.0	0.0	0.0	682	755.73	299.28	1055.00
9	97	73.3	0	0.0	0	0.0	0.0	0.0	370	1029.99	372.67	1402.66
10	76	75.2	152	62.81	76	57.38	147.06	110.89	684	782.94	255.39	1038.23
11	37	76.8	148	61.15	74	82.93	145.50	107.23	296	355.09	110.60	465.69
12	3	78.1	18	7.44	9	13.58	19.29	13.41	21	25.23	7.73	32.76
13												
14												
15												
TOTALS	501	-----	318	131.40	159	153.96	311.85	231.53	3370	3635.01	1316.23	4951.23

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
116	40	3	0	0	0	0	0

continued

Table 1.—Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 26 SITE INDEX: 70 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 600

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3	6	42.5	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
4	27	51.5	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
5	59	57.8	0	0.0	0	0.0	0.0	0.0	118	73.05	38.43	111.47
6	93	62.4	0	0.0	0	0.0	0.0	0.0	465	289.99	125.33	415.22
7	118	65.9	0	0.0	0	0.0	0.0	0.0	826	614.96	246.26	861.23
8	123	68.6	0	0.0	0	0.0	0.0	0.0	1107	931.74	353.75	1285.49
9	103	70.9	0	0.0	0	0.0	0.0	0.0	927	1060.00	385.29	1445.29
10	59	72.7	118	48.76	59	44.16	114.41	5.97	472	582.45	190.66	773.11
11	11	74.2	44	18.18	22	24.30	43.36	31.74	77	99.91	31.23	131.04
12												
13												
14												
15												
TOTALS	599	-----	162	66.94	81	68.45	157.77	117.72	3992	3651.92	1370.96	5022.85

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
7	11	[illegible]					

continued

Table 1.—Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 16 SITE INDEX: 80 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 200

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3												
4												
5	2	46.9	0	0.0	0	0.0	0.0	0.0	4	2.23	1.19	3.42
6	10	50.6	0	0.0	0	0.0	0.0	0.0	50	26.40	11.85	38.25
7	23	53.5	0	0.0	0	0.0	0.0	0.0	138	99.79	41.41	141.20
8	36	55.7	0	0.0	0	0.0	0.0	0.0	252	225.77	88.52	314.29
9	45	57.5	0	0.0	0	0.0	0.0	0.0	360	382.37	143.15	525.52
10	44	59.0	88	36.36	44	30.92	86.61	63.57	308	331.71	111.27	442.97
11	31	60.3	124	51.24	62	61.57	124.21	87.07	155	193.73	62.88	256.61
12	8	61.3	32	13.22	16	25.66	34.90	26.40	48	62.88	19.79	82.67
13												
14												
15												
TOTALS	199	-----	244	100.82	122	118.14	245.71	177.05	1315	1324.87	480.06	1804.93

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
75	39	8	0	0	0	0	0

continued

Table 1.—Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 18 SITE INDEX: 80 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 200

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3												
4												
5	2	50.6	0	0.0	0	0.0	0.0	0.0	4	2.31	1.23	3.54
6	8	54.6	0	0.0	0	0.0	0.0	0.0	40	22.43	9.93	32.36
7	19	57.7	0	0.0	0	0.0	0.0	0.0	114	88.09	36.07	124.16
8	30	60.1	0	0.0	0	0.0	0.0	0.0	210	201.49	78.06	279.55
9	40	62.1	0	0.0	0	0.0	0.0	0.0	320	364.36	134.91	499.27
10	43	63.7	86	35.53	43	30.98	84.15	62.33	301	358.35	119.06	477.41
11	37	65.0	148	61.15	74	76.71	147.34	104.97	222	266.55	85.25	351.80
12	20	66.2	120	49.58	60	81.10	123.57	86.59	100	112.55	36.26	148.81
13	2	67.1	12	4.96	6	12.07	13.23	10.08	10	14.00	4.37	18.37
14												
15												
TOTALS	201	-----	366	151.23	183	200.87	368.29	263.96	1321	1430.14	505.13	1935.27

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
100	59	22	2	0	0	0	0

continued

Table 1.—Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 20 SITE INDEX: 80 (50 YEAR BASIS) NUMBER OF SURVIVING TREES: 201

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3												
4												
5	2	58.8	0	0.0	0	0.0	0.0	0.0	4	2.39	1.26	3.65
6	7	58.1	0	0.0	0	0.0	0.0	0.0	35	20.60	9.02	29.62
7	16	61.3	0	0.0	0	0.0	0.0	0.0	112	78.27	31.72	109.99
8	26	63.9	0	0.0	0	0.0	0.0	0.0	208	184.54	70.83	255.37
9	36	66.0	0	0.0	0	0.0	0.0	0.0	324	346.76	127.28	474.04
10	41	67.7	82	33.89	41	30.09	79.89	59.57	328	369.66	121.95	491.61
11	38	69.1	152	62.81	76	81.24	150.60	108.66	266	305.11	96.55	401.66
12	27	70.3	162	66.94	81	114.40	166.01	118.29	135	176.96	56.05	233.01
13	8	71.4	48	19.83	24	50.17	52.45	40.80	48	65.02	19.96	84.98
14												
15												
TOTALS	201	-----	444	183.46	222	275.89	448.95	327.33	1460	1549.30	534.63	2083.93

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
106	73	35	8	0	0	0	0

continued

Table 1.—Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 22 SITE INDEX: 90 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 200

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3												
4												
5	1	56.5	0	0.0	0	0.0	0.0	0.0	2	1.22	0.65	1.87
6	6	61.0	0	0.0	0	0.0	0.0	0.0	30	18.37	7.97	26.35
7	14	64.4	0	0.0	0	0.0	0.0	0.0	98	71.55	28.76	100.31
8	23	67.1	0	0.0	0	0.0	0.0	0.0	184	170.81	65.06	235.88
9	33	69.3	0	0.0	0	0.0	0.0	0.0	297	332.81	121.33	454.14
10	39	71.1	78	32.23	33	29.02	75.74	56.78	312	374.63	122.92	497.56
11	39	72.6	156	64.45	78	85.33	153.99	112.24	273	341.11	107.09	448.20
12	31	73.9	186	76.85	93	135.71	189.82	137.12	186	228.43	71.44	299.87
13	14	75.0	112	46.28	56	101.26	117.85	85.94	70	78.48	25.02	103.50
14	1	75.9	8	3.31	4	10.10	8.88	7.07	5	6.89	2.13	9.02
15												
TOTALS	201	-----	540	223.12	270	361.42	546.28	399.04	1457	1624.33	552.37	2176.70

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
123	85	46	15	1	0	0	0

continued

Table 1.—Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 24 SITE INDEX: 80 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 200

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3												
4												
5	1	58.9	0	0.0	0	0.0	0.0	0.0	3	1.25	0.66	1.91
6	5	63.6	0	0.0	0	0.0	0.0	0.0	30	15.84	6.82	22.66
7	12	67.2	0	0.0	0	0.0	0.0	0.0	96	63.65	25.41	89.06
8	21	70.0	0	0.0	0	0.0	0.0	0.0	189	161.96	61.31	223.27
9	30	72.3	0	0.0	0	0.0	0.0	0.0	300	314.40	113.97	428.37
10	37	74.1	74	30.58	37	27.83	71.66	53.96	333	374.45	122.33	496.78
11	38	75.7	152	62.81	76	84.65	149.59	109.93	304	356.31	111.20	467.51
12	33	77.0	198	81.81	99	148.15	201.38	147.12	198	267.00	82.70	349.71
13	19	78.2	152	62.81	76	142.06	159.39	117.70	95	121.11	38.07	159.18
14	3	79.2	24	9.92	12	31.22	26.47	21.43	18	23.46	7.14	30.60
15												
TOTALS	199	———	600	247.92	300	433.92	608.47	450.14	1566	1699.44	569.61	2269.06

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
127	93	55	22	3	0	0	0

continued

Table 1.—Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 26 SITE INDEX: 80 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 200

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3												
4												
5	1	61.0	0	0.0	0	0.0	0.0	0.0	3	1.28	0.67	1.94
6	5	65.9	0	0.0	0	0.0	0.0	0.0	30	16.29	6.97	23.26
7	11	69.6	0	0.0	0	0.0	0.0	0.0	88	60.19	23.89	84.07
8	20	72.5	0	0.0	0	0.0	0.0	0.0	180	159.30	60.00	219.30
9	28	74.8	0	0.0	0	0.0	0.0	0.0	280	303.15	109.38	412.52
10	35	76.8	70	28.92	35	26.56	67.64	51.11	315	370.03	120.46	490.49
11	37	78.4	148	61.15	74	83.61	145.29	107.51	296	367.42	114.11	481.53
12	34	79.8	204	84.29	102	155.73	206.88	152.57	238	296.84	91.24	388.07
13	23	81.0	184	76.03	92	176.54	192.33	143.71	138	162.56	50.54	213.10
14	6	82.0	60	24.79	30	68.43	64.30	49.08	24	30.79	9.80	40.59
15												
TOTALS	200	———	666	275.19	333	510.88	676.43	503.98	1592	1767.83	587.04	2354.87

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
135	100	63	29	6	0	0	0

continued

Table 1.—Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 28 SITE INDEX: 80 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 200

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3												
4												
5	1	62.9	0	0.0	0	0.0	0.0	0.0	3	1.30	0.68	1.97
6	4	67.9	0	0.0	0	0.0	0.0	0.0	24	13.35	5.69	19.05
7	10	71.7	0	0.0	0	0.0	0.0	0.0	80	56.21	22.20	78.41
8	18	74.7	0	0.0	0	0.0	0.0	0.0	162	147.39	55.27	202.66
9	27	77.1	0	0.0	0	0.0	0.0	0.0	270	300.66	108.05	408.71
10	33	79.1	66	27.27	33	25.23	63.65	48.24	297	362.16	117.56	479.71
11	37	80.8	148	61.15	74	84.60	144.98	107.91	296	385.69	119.32	505.01
12	34	82.2	204	84.29	102	158.28	206.36	153.43	238	316.31	96.63	412.94
13	25	83.4	200	82.64	100	196.01	208.46	157.33	150	192.33	59.27	251.60
14	10	84.5	100	41.32	50	117.13	106.90	82.56	50	57.65	18.14	75.79
15												
TOTALS	199	-----	718	296.67	359	581.25	730.36	549.48	1570	1833.04	602.79	2435.83

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
80	165	69	35	10	0	0	0

continued

Table 1.—Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 30 SITE INDEX: 80 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 200

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3												
4												
5	1	64.5	0	0.0	0	0.0	0.0	0.0	3	1.32	0.69	2.00
6	4	69.7	0	0.0	0	0.0	0.0	0.0	24	13.64	5.79	19.43
7	10	73.6	0	0.0	0	0.0	0.0	0.0	80	57.55	22.64	80.18
8	17	76.7	0	0.0	0	0.0	0.0	0.0	170	142.58	53.27	195.84
9	25	79.2	0	0.0	0	0.0	0.0	0.0	275	285.21	102.15	387.36
10	32	81.2	64	26.44	32	24.61	61.63	46.82	320	362.66	117.43	480.09
11	36	82.9	144	59.50	72	83.13	140.81	105.33	324	391.13	120.62	511.75
12	35	84.4	210	86.77	105	165.15	211.98	158.70	280	343.60	104.43	448.03
13	27	85.6	216	89.25	108	215.44	224.58	170.97	162	222.99	68.21	291.19
14	13	86.7	130	53.72	65	155.65	132.62	108.17	65	82.46	25.69	108.15
15	1	87.7	10	4.13	5	15.90	11.10	9.51	5	7.70	2.32	10.03
TOTALS	201	———	774	319.81	387	659.87	788.72	599.51	1708	1910.82	623.22	2534.05

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
81	174	76	41	15	0	0	0

continued

Table 1.—Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 16 SITE INDEX: 80 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 300

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3												
4	2	42.8	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
5	12	48.0	0	0.0	0	0.0	0.0	0.0	24	13.51	7.22	20.73
6	31	51.8	0	0.0	0	0.0	0.0	0.0	155	83.26	37.22	120.48
7	53	54.7	0	0.0	0	0.0	0.0	0.0	318	234.44	96.91	331.35
8	68	57.0	0	0.0	0	0.0	0.0	0.0	476	435.10	169.99	605.10
9	68	58.8	0	0.0	0	0.0	0.0	0.0	544	589.78	220.08	809.86
10	49	60.4	98	40.49	49	34.69	96.28	70.86	343	380.50	127.26	507.77
11	16	61.6	64	26.44	32	32.20	63.99	45.07	96	104.35	33.72	138.07
12												
13												
14												
15												
TOTALS	299	———	162	66.94	81	66.89	160.27	115.94	1956	1840.95	692.40	2533.35

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
65	16	0	0	0	0	0	0

continued

Table 1.— Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 18 SITE INDEX: 80 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 300

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3												
4	1	46.1	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
5	10	51.7	0	0.0	0	0.0	0.0	0.0	20	11.70	6.21	17.91
6	25	55.9	0	0.0	0	0.0	0.0	0.0	125	71.34	31.45	102.79
7	44	59.0	0	0.0	0	0.0	0.0	0.0	308	208.01	84.85	292.87
8	60	61.5	0	0.0	0	0.0	0.0	0.0	480	411.21	158.75	569.96
9	66	63.5	0	0.0	0	0.0	0.0	0.0	528	613.73	226.52	840.25
10	57	65.1	114	47.10	57	41.35	111.37	82.69	399	499.07	162.07	651.14
11	32	66.5	128	52.89	64	67.12	127.20	91.05	192	240.04	76.47	316.51
12	4	67.7	24	9.92	12	16.49	24.67	17.39	20	23.84	7.63	31.46
13												
14												
15												
TOTALS	299	-----	266	109.91	133	124.96	263.24	191.14	2072	2068.93	753.95	2822.88

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
93	36	4	0	0	[illegible]	[illegible]	[illegible]

continued

Table 1.—Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 20 SITE INDEX: 80 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 300

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3												
4	1	49.0	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
5	8	55.0	0	0.0	0	0.0	0.0	0.0	16	9.66	5.10	14.76
6	21	59.4	0	0.0	0	0.0	0.0	0.0	105	62.90	27.43	90.33
7	38	62.7	0	0.0	0	0.0	0.0	0.0	266	189.57	76.54	266.10
8	54	65.3	0	0.0	0	0.0	0.0	0.0	432	391.14	149.60	540.74
9	63	67.5	0	0.0	0	0.0	0.0	0.0	567	619.52	226.71	846.23
10	59	69.2	118	48.76	59	43.57	114.79	85.81	472	547.30	180.10	727.40
11	42	70.7	168	69.42	84	90.75	166.18	120.45	294	350.58	110.55	461.13
12	14	71.9	84	34.71	42	60.22	85.92	61.60	84	96.77	30.47	127.24
13												
14												
15												
TOTALS	300	-----	370	152.88	185	194.54	366.88	267.85	2236	2267.44	806.49	3073.93

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
115	56	14	0	0	0	0	0

continued

Table 1.—Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 22 SITE INDEX: 80 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 300

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3												
4	1	51.5	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
5	7	57.8	0	0.0	0	0.0	0.0	0.0	14	8.67	4.56	13.23
6	19	62.4	0	0.0	0	0.0	0.0	0.0	95	59.26	25.62	84.87
7	34	65.9	0	0.0	0	0.0	0.0	0.0	238	177.29	70.99	248.28
8	49	68.7	0	0.0	0	0.0	0.0	0.0	441	371.39	140.99	512.38
9	59	70.9	0	0.0	0	0.0	0.0	0.0	531	607.53	220.81	828.33
10	60	72.7	120	49.58	60	44.91	116.35	87.43	480	592.77	194.03	786.80
11	47	74.3	188	77.68	94	103.85	185.27	135.64	329	426.87	133.58	560.45
12	23	75.6	138	57.02	69	102.09	159.53	102.36	138	178.32	55.48	233.80
13	1	76.7	8	3.31	4	7.37	9.40	6.17	5	6.04	1.90	7.92
14												
15												
TOTALS	300	———	454	187.59	227	258.21	469.64	331.60	2271	2428.12	847.95	3276.07

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
131	71	25	1	0	0	2	1

continued

Table 1.—Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 24 SITE INDEX: 80 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 300

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3												
4	1	53.7	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
5	6	60.2	0	0.0	0	0.0	0.0	0.0	18	7.60	3.98	11.58
6	17	65.0	0	0.0	0	0.0	0.0	0.0	102	54.80	23.52	78.33
7	31	68.7	0	0.0	0	0.0	0.0	0.0	248	167.71	66.70	234.41
8	45	71.6	0	0.0	0	0.0	0.0	0.0	405	354.22	133.65	487.87
9	56	73.9	0	0.0	0	0.0	0.0	0.0	560	599.24	216.58	815.82
10	59	75.8	118	48.76	59	44.63	114.10	86.11	531	614.05	200.16	814.21
11	50	77.4	200	82.64	100	112.41	196.51	145.05	400	486.41	151.33	637.74
12	30	78.8	180	74.37	90	136.43	182.73	134.30	210	254.82	78.54	333.36
13	5	79.9	40	16.53	20	38.02	41.86	31.14	25	34.06	10.63	44.69
14												
15												
TOTALS	300	———	538	222.30	269	331.50	535.20	396.61	2499	2572.92	885.09	3458.01

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
144	85	35	5	0	0	0	0

continued

Table 1.—Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 26 SITE INDEX: 80 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 300

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3												
4	1	55.6	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
5	5	62.4	0	0.0	0	0.0	0.0	0.0	15	6.46	3.38	9.83
6	15	67.4	0	0.0	0	0.0	0.0	0.0	90	49.76	21.23	70.99
7	28	71.1	0	0.0	0	0.0	0.0	0.0	224	156.32	61.82	218.14
8	42	74.1	0	0.0	0	0.0	0.0	0.0	378	341.45	128.18	469.63
9	53	76.5	0	0.0	0	0.0	0.0	0.0	530	585.92	210.79	796.71
10	58	78.5	116	47.93	58	64.26	111.93	94.76	522	630.45	204.79	835.25
11	52	80.2	208	85.94	104	118.55	203.87	151.51	416	535.37	165.79	701.15
12	35	81.6	210	86.77	105	162.27	212.57	157.72	245	320.39	98.02	418.41
13	10	82.8	80	33.06	40	77.99	83.45	62.82	60	75.30	23.26	98.55
14												
15												
TOTALS	299	-----	614	253.70	307	403.06	611.81	456.81	2480	2701.41	917.25	3618.66

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
120	132	45	10	0	0	0	0

continued

Table 1.—Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 28 SITE INDEX: 80 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 300

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D. B. H. CLASS	TREES	MEAN TREE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3												
4	1	57.3	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
5	5	64.3	0	0.0	0	0.0	0.0	0.0	15	6.56	3.42	9.99
6	14	69.4	0	0.0	0	0.0	0.0	0.0	84	47.61	20.21	67.82
7	26	73.3	0	0.0	0	0.0	0.0	0.0	208	149.11	58.69	207.80
8	40	76.4	0	0.0	0	0.0	0.0	0.0	400	334.32	124.97	459.28
9	51	78.9	0	0.0	0	0.0	0.0	0.0	561	579.80	207.77	787.56
10	56	80.9	112	46.28	56	43.03	107.88	81.93	560	631.75	204.64	836.39
11	53	82.6	212	87.60	106	122.21	207.36	155.00	477	572.46	176.61	749.08
12	39	84.1	234	96.69	117	183.67	236.28	176.72	312	379.96	115.57	495.53
13	15	85.3	120	49.58	60	119.39	124.81	94.90	90	122.65	37.56	160.21
14												
15												
TOTALS	300	-----	678	280.15	339	468.31	676.33	508.55	2707	2824.22	949.42	3773.65

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
109	161	54	15	0	0	0	0

continued

Table 1.—Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 30 SITE INDEX: 80 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 300

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3												
4	1	58.8	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
5	5	66.0	0	0.0	0	0.0	0.0	0.0	15	6.67	3.47	10.14
6	13	71.2	0	0.0	0	0.0	0.0	0.0	78	45.15	19.09	64.24
7	25	75.2	0	0.0	0	0.0	0.0	0.0	200	146.75	57.52	204.27
8	38	78.4	0	0.0	0	0.0	0.0	0.0	380	325.31	121.15	446.47
9	49	80.9	0	0.0	0	0.0	0.0	0.0	539	570.72	203.83	774.56
10	55	83.0	110	45.45	55	42.51	105.79	80.54	550	640.50	206.97	847.47
11	53	84.8	212	87.60	106	123.37	207.00	155.49	477	596.26	183.38	779.65
12	41	86.3	246	101.65	123	195.62	247.87	186.67	329	420.99	127.41	548.40
13	20	87.6	160	66.11	80	161.90	165.99	127.31	140	175.17	53.25	228.42
14	1	88.7	10	4.13	5	12.19	10.64	8.38	5	6.86	2.12	8.99
15												
TOTALS	301	-----	738	304.94	369	535.60	737.29	558.39	2712	2934.40	978.19	3912.60

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
109	176	62	21	1	0	0	0

continued

Table 1.— Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 18 SITE INDEX: [illegible] (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 436

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3												
4	6	47.2	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
5	24	52.9	0	0.0	0	0.0	0.0	0.0	48	28.40	15.05	43.45
6	49	57.1	0	0.0	0	0.0	0.0	0.0	245	142.30	62.48	204.79
7	74	60.3	0	0.0	0	0.0	0.0	0.0	518	356.46	145.02	501.89
8	88	62.9	0	0.0	0	0.0	0.0	0.0	704	615.43	236.77	852.20
9	83	64.9	0	0.0	0	0.0	0.0	0.0	747	787.77	289.83	1077.60
10	57	66.6	114	47.10	57	41.63	111.19	82.77	456	503.34	166.36	669.69
11	19	68.0	72	29.75	36	38.18	71.43	51.36	108	140.48	44.57	185.05
12												
13												
14												
15												
TOTALS	399	———	186	76.85	93	79.81	182.62	134.13	2326	2574.57	960.09	3534.66

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
75	18	0	0	0	0	0	0

continued

Table 1.—Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 20 SITE INDEX: 80 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 400

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3												
4	5	50.1	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
5	20	56.2	0	0.0	0	0.0	0.0	0.0	40	24.42	12.88	37.30
6	42	60.7	0	0.0	0	0.0	0.0	0.0	210	128.11	55.65	183.76
7	66	64.1	0	0.0	0	0.0	0.0	0.0	462	335.90	135.11	471.01
8	82	66.8	0	0.0	0	0.0	0.0	0.0	656	606.14	231.06	837.20
9	84	69.0	0	0.0	0	0.0	0.0	0.0	756	843.18	307.59	1150.77
10	66	70.8	132	54.54	66	49.04	128.21	96.07	528	629.93	206.80	836.72
11	32	72.3	128	52.89	64	59.85	126.40	92.03	224	277.48	87.18	364.66
12	3	73.5	18	7.44	9	13.09	18.38	13.26	18	21.85	6.84	28.69
13												
14												
15												
TOTALS	400	-----	278	114.87	139	131.99	272.99	201.36	2894	2867.00	1043.10	3910.11

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
101	35	3	0	0	0	0	0

continued

Table 1.—Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 22 SITE INDEX: 80 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 400

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3												
4	4	52.7	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
5	17	59.1	0	0.0	0	0.0	0.0	0.0	51	21.32	11.20	32.52
6	37	63.8	0	0.0	0	0.0	0.0	0.0	222	117.45	50.58	168.03
7	59	67.4	0	0.0	0	0.0	0.0	0.0	472	313.77	125.17	438.94
8	76	70.2	0	0.0	0	0.0	0.0	0.0	684	587.90	222.45	810.34
9	82	72.5	0	0.0	0	0.0	0.0	0.0	820	861.95	312.32	1174.27
10	71	74.4	142	58.67	71	53.45	137.48	103.55	639	721.46	235.61	957.07
11	43	75.9	172	71.07	86	95.92	169.23	124.45	344	405.35	126.44	531.79
12	9	77.3	54	22.31	27	40.48	54.91	40.15	54	73.34	22.70	96.04
13												
14												
15												
TOTALS	398	-----	368	152.06	184	189.85	361.61	268.14	3286	3102.54	1106.47	4209.01

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
123	52	9	0	0	0	0	0

continued

AGE: 24 SITE INDEX: 80 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 400

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3												
4	4	54.9	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
5	15	61.6	0	0.0	0	0.0	0.0	0.0	45	19.24	10.07	29.31
6	34	66.5	0	0.0	0	0.0	0.0	0.0	204	111.64	47.73	159.37
7	54	70.2	0	0.0	0	0.0	0.0	0.0	432	298.08	118.12	416.20
8	72	73.2	0	0.0	0	0.0	0.0	0.0	648	578.46	217.55	796.01
9	80	75.6	0	0.0	0	0.0	0.0	0.0	800	873.94	314.93	1188.86
10	73	77.5	146	60.33	73	55.53	140.99	106.63	657	781.05	254.02	1035.07
11	51	79.2	204	84.29	102	115.69	200.13	148.37	408	514.39	159.55	673.95
12	17	80.5	102	42.15	51	78.28	103.36	76.42	119	151.49	46.47	197.95
13												
14												
15												
TOTALS	400	-----	452	186.76	226	249.50	444.47	331.42	3313	3329.28	1168.44	4496.71

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
124	85	17	0	0	0	0	0

continued

Table 1.—Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 26 SITE INDEX: 80 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 400

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3												
4	3	56.9	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
5	14	63.8	0	0.0	0	0.0	0.0	0.0	42	18.31	9.55	27.86
6	31	68.9	0	0.0	0	0.0	0.0	0.0	186	104.75	44.52	149.27
7	50	72.8	0	0.0	0	0.0	0.0	0.0	400	284.72	112.19	396.92
8	68	75.8	0	0.0	0	0.0	0.0	0.0	680	564.27	211.15	775.41
9	77	78.3	0	0.0	0	0.0	0.0	0.0	770	869.06	311.73	1180.79
10	74	80.3	148	61.15	74	56.76	142.62	108.24	740	826.90	268.04	1094.94
11	56	82.0	224	92.56	112	128.76	219.22	163.62	504	597.50	184.51	782.01
12	25	83.4	150	61.98	75	117.27	151.56	113.12	175	239.73	73.02	312.75
13	1	84.7	8	3.31	4	7.92	8.33	6.32	6	8.01	2.46	10.46
14												
15												
TOTALS	399	-----	530	218.99	265	310.71	521.71	391.29	3503	3513.23	1217.18	4730.41

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
130	108	26	1	0	0	0	0

continued

Table 1.—Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 28 SITE INDEX: 80 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 400

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3												
4	3	58.6	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
5	13	65.7	0	0.0	0	0.0	0.0	0.0	39	17.28	9.00	26.27
6	28	71.0	0	0.0	0	0.0	0.0	0.0	168	96.93	41.00	137.92
7	47	75.0	0	0.0	0	0.0	0.0	0.0	376	275.05	107.87	382.93
8	64	78.1	0	0.0	0	0.0	0.0	0.0	640	546.00	203.45	749.45
9	75	80.6	0	0.0	0	0.0	0.0	0.0	825	870.69	311.12	1181.81
10	75	82.7	150	61.98	75	57.92	144.29	109.82	750	869.45	281.04	1150.49
11	60	84.5	240	99.17	120	139.48	234.40	175.95	540	671.10	206.49	877.59
12	31	86.0	186	76.85	93	147.64	187.47	141.05	248	316.02	95.72	411.74
13	3	87.2	24	9.92	12	24.23	24.91	19.08	21	26.02	7.92	33.94
14												
15												
TOTALS	399	———	600	247.92	300	369.27	591.07	445.89	3607	3688.54	1263.60	4952.14

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
135	128	34	3	0	0	0	0

continued

Table 1.—Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 30 SITE INDEX: 80 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 400

D.B.H. CLASS	TREES	MEAN TREE HEIGHT	PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
			STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3												
4	3	50.2	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
5	12	67.5	0	0.0	0	0.0	0.0	0.0	36	15.20	9.42	24.62
6	27	72.9	0	0.0	0	0.0	0.0	0.0	167	85.52	49.23	135.75
7	45	76.9	0	0.0	0	0.0	0.0	0.0	405	263.56	105.29	374.85
8	52	80.2	0	0.0	0	0.0	0.0	0.0	520	541.80	201.15	742.95
9	73	82.8	0	0.0	0	0.0	0.0	0.0	483	868.29	309.24	1177.53
10	74	84.9	148	61.15	74	57.48	142.15	138.46	740	885.60	285.61	1171.20
11	62	86.7	248	102.47	124	145.46	241.80	182.33	558	721.14	221.54	943.68
12	36	88.2	288	119.03	144	199.03	280.27	137.43	252	258.24	93.63	351.87
13	6	89.5	48	19.83	24	49.25	49.69	38.39	42	55.66	16.82	72.48
14												
15												
TOTALS	400	-----	732	302.46	366	451.22	713.91	526.66	3518	3723.02	1271.92	4994.93

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
172	140	48	6	0	0	0	0

continued

Table 1.— Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 18 SITE INDEX: 80 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 500

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3	2	39.8	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
4	15	48.2	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
5	43	54.1	0	0.0	0	0.0	0.0	0.0	86	51.47	27.22	78.69
6	78	58.4	0	0.0	0	0.0	0.0	0.0	390	230.68	100.88	331.56
7	104	61.7	0	0.0	0	0.0	0.0	0.0	728	511.45	207.05	718.50
8	111	64.3	0	0.0	0	0.0	0.0	0.0	888	792.17	303.72	1095.89
9	91	66.4	0	0.0	0	0.0	0.0	0.0	819	881.58	323.32	1204.91
10	49	68.1	98	40.49	49	36.02	95.44	71.22	392	445.33	146.82	592.15
11	7	69.5	28	11.57	14	15.01	27.73	20.03	49	56.82	17.96	74.78
12												
13												
14												
15												
TOTALS	500	-----	126	52.06	63	51.03	123.17	91.25	3352	2969.49	1126.99	4096.48

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
56	7	0	0	0	0	0	0

continued

Table 1.—Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 20 SITE INDEX: 80 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 500

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3	1	42.3	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
4	12	51.3	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
5	37	57.5	0	0.0	0	0.0	0.0	0.0	74	45.69	24.05	69.74
6	68	62.1	0	0.0	0	0.0	0.0	0.0	340	211.11	91.35	302.46
7	95	65.6	0	0.0	0	0.0	0.0	0.0	665	493.09	197.60	690.68
8	107	68.3	0	0.0	0	0.0	0.0	0.0	963	807.20	306.67	1113.87
9	97	70.5	0	0.0	0	0.0	0.0	0.0	873	994.11	361.56	1355.67
10	64	72.4	128	52.89	64	47.84	124.14	93.24	512	628.39	205.81	834.19
11	20	73.9	80	33.06	40	44.09	78.87	57.69	140	190.11	56.40	236.51
12												
13												
14												
15												
TOTALS	501	———	208	85.94	104	91.94	203.01	150.93	3567	3359.70	1243.43	4603.13

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
84	20	0	0	0	0	0	0

continued

Table 1.—Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 22 SITE INDEX: 80 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 500

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3	1	44.5	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
4	11	53.9	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
5	32	60.4	0	0.0	0	0.0	0.0	0.0	96	40.59	21.28	61.87
6	60	65.2	0	0.0	0	0.0	0.0	0.0	360	193.99	83.22	277.20
7	87	68.9	0	0.0	0	0.0	0.0	0.0	696	472.06	187.64	659.71
8	102	71.8	0	0.0	0	0.0	0.0	0.0	918	805.30	303.70	1109.00
9	99	74.1	0	0.0	0	0.0	0.0	0.0	891	1062.56	383.88	1446.44
10	74	76.0	148	61.15	74	56.03	143.09	108.02	666	773.27	251.98	1025.25
11	33	77.7	132	54.54	66	74.29	129.67	95.77	264	322.73	100.36	423.09
12	2	79.0	12	4.96	6	9.11	12.18	8.96	14	17.11	5.27	22.38
13												
14												
15												
TOTALS	501	-----	292	120.65	146	139.43	284.93	212.75	4304	3687.61	1337.32	5024.93

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
103	35	2	0	0	0	0	0

continued

Table 1.—Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 24 SITE INDEX: 80 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 500

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3	1	46.4	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
4	9	56.2	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
5	29	63.0	0	0.0	0	0.0	0.0	0.0	87	37.66	19.67	57.33
6	55	68.0	0	0.0	0	0.0	0.0	0.0	330	183.93	78.35	262.29
7	81	71.8	0	0.0	0	0.0	0.0	0.0	648	456.05	180.07	636.12
8	98	74.8	0	0.0	0	0.0	0.0	0.0	882	803.84	301.35	1105.20
9	99	77.3	0	0.0	0	0.0	0.0	0.0	990	1104.33	396.80	1501.13
10	80	79.3	160	66.11	80	61.18	154.30	116.96	720	879.99	285.59	1165.58
11	43	80.9	172	71.07	86	98.39	168.47	125.44	344	443.57	139.05	588.62
12	6	82.4	36	14.87	18	27.96	36.41	27.09	42	56.04	17.11	73.15
13												
14												
15												
TOTALS	501	———	368	152.06	184	187.53	359.18	269.48	4043	3971.42	1417.99	5389.41

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
123	55	6	0	0	0	0	0

continued

Table 1.—Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 26 SITE INDEX: 80 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 500

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3	1	48.0	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
4	8	58.2	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
5	26	65.2	0	0.0	0	0.0	0.0	0.0	78	34.42	17.93	52.35
6	50	70.4	0	0.0	0	0.0	0.0	0.0	300	171.98	72.83	244.81
7	75	74.4	0	0.0	0	0.0	0.0	0.0	600	435.80	171.12	606.92
8	94	77.5	0	0.0	0	0.0	0.0	0.0	940	796.19	296.99	1093.18
9	98	80.0	0	0.0	0	0.0	0.0	0.0	1079	1129.48	403.99	1533.47
10	84	82.1	168	69.42	84	64.76	161.68	122.96	840	964.59	312.01	1276.60
11	51	83.8	204	84.29	102	118.23	139.34	149.41	459	563.69	173.61	737.30
12	12	85.3	72	29.75	36	56.93	72.62	54.52	96	120.44	36.53	156.97
13												
14												
15												
TOTALS	439	-----	444	183.46	222	239.92	433.63	326.90	4391	4216.58	1485.02	5701.60

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
135	75	12	0	0	0	0	0

continued

Table 1.—Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 28 SITE INDEX: 80 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 500

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3	1	49.5	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
4	8	59.9	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
5	24	67.2	0	0.0	0	0.0	0.0	0.0	72	32.34	16.80	49.15
6	47	72.6	0	0.0	0	0.0	0.0	0.0	282	165.72	69.84	235.56
7	71	76.7	0	0.0	0	0.0	0.0	0.0	639	423.84	165.65	589.49
8	90	79.9	0	0.0	0	0.0	0.0	0.0	900	783.76	291.13	1074.89
9	97	82.5	0	0.0	0	0.0	0.0	0.0	1067	1149.73	409.66	1559.39
10	86	84.6	172	71.07	86	66.75	165.24	126.03	860	1024.56	330.52	1355.08
11	58	86.4	232	95.86	116	135.90	226.25	170.54	522	671.68	206.14	877.82
12	19	87.9	152	62.81	76	104.77	147.94	104.11	114	140.21	43.76	183.97
13												
14												
15												
TOTALS	501	———	556	229.74	278	307.42	539.43	400.67	4456	4391.84	1533.50	5925.34

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
163	96	19	0	0	0	0	0

continued

Table 1.—Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 30 SITE INDEX: 80 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 500

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3	1	50.8	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
4	7	61.5	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
5	22	69.0	0	0.0	0	0.0	0.0	0.0	66	30.07	15.59	45.66
6	44	74.5	0	0.0	0	0.0	0.0	0.0	264	158.47	66.50	224.97
7	68	78.7	0	0.0	0	0.0	0.0	0.0	612	415.67	161.81	577.48
8	87	82.0	0	0.0	0	0.0	0.0	0.0	870	776.29	287.33	1063.62
9	95	84.6	0	0.0	0	0.0	0.0	0.0	1045	1153.95	409.84	1563.79
10	88	86.8	176	72.72	88	68.68	168.84	129.08	968	1081.90	348.22	1430.13
11	63	88.7	252	104.12	126	148.94	245.34	185.82	630	759.41	232.41	991.83
12	25	90.2	200	82.64	100	140.36	194.47	137.80	175	197.25	61.12	258.37
13	1	91.6	10	4.13	5	9.03	10.07	7.35	6	6.47	2.03	8.50
14												
15												
TOTALS	501	-----	638	263.62	319	367.01	618.72	460.05	4536	4579.48	1584.87	6164.34

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
177	114	27	1	0	0	0	0

continued

Table 1.— Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 20 SITE INDEX: 80 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 600

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D. B. H. CLASS	TREES	MEAN TREE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3	4	43.3	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
4	23	52.4	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
5	58	58.8	0	0.0	0	0.0	0.0	0.0	174	72.53	38.10	110.63
6	95	63.5	0	0.0	0	0.0	0.0	0.0	570	300.38	129.47	429.84
7	122	67.1	0	0.0	0	0.0	0.0	0.0	976	646.04	257.95	904.00
8	127	69.9	0	0.0	0	0.0	0.0	0.0	1143	977.81	370.25	1348.06
9	103	72.1	0	0.0	0	0.0	0.0	0.0	1030	1077.58	390.72	1468.31
10	57	74.0	114	47.10	57	42.86	110.41	83.12	513	575.52	188.05	763.57
11	11	75.6	44	18.18	22	24.48	43.31	31.82	88	102.83	32.10	134.92
12												
13												
14												
15												
TOTALS	600	-----	158	65.28	79	67.34	153.71	114.93	4494	3752.70	1406.64	5159.33

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
68	11	0	0	0	0	0	0

continued

Table 1.—Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 22 SITE INDEX: 80 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 600

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3	3	45.5	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
4	20	55.1	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
5	51	61.8	0	0.0	0	0.0	0.0	0.0	153	65.51	34.27	99.78
6	86	66.7	0	0.0	0	0.0	0.0	0.0	516	283.03	120.96	403.98
7	114	70.5	0	0.0	0	0.0	0.0	0.0	912	630.91	249.87	880.78
8	124	73.4	0	0.0	0	0.0	0.0	0.0	1116	999.21	375.62	1374.83
9	109	75.8	0	0.0	0	0.0	0.0	0.0	1090	1194.33	430.20	1624.53
10	70	77.8	140	57.85	70	53.29	135.17	102.26	630	751.96	244.48	996.44
11	22	79.4	88	36.36	44	49.97	86.31	64.03	176	223.05	69.16	292.21
12												
13												
14												
15												
TOTALS	599	———	228	94.21	114	103.26	221.47	166.29	4593	4147.98	1524.55	5672.54

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
92	22	0	0	0	0	0	0

continued

Table 1.—Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 24 SITE INDEX: 80 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 600

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3	3	47.4	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
4	18	57.4	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
5	46	64.4	0	0.0	0	0.0	0.0	0.0	138	60.49	31.54	92.02
6	79	69.5	0	0.0	0	0.0	0.0	0.0	474	268.94	114.14	383.07
7	107	73.5	0	0.0	0	0.0	0.0	0.0	856	614.72	241.86	856.58
8	121	76.5	0	0.0	0	0.0	0.0	0.0	1210	1013.06	378.58	1391.64
9	112	79.0	0	0.0	0	0.0	0.0	0.0	1232	1275.51	456.96	1732.47
10	80	81.1	160	66.11	80	61.50	154.09	117.05	800	904.57	292.96	1197.54
11	33	82.8	132	54.54	66	76.15	129.10	96.53	297	357.49	110.27	467.76
12	2	84.2	12	4.96	6	9.43	12.12	9.07	16	19.56	5.95	25.51
13												
14												
15												
TOTALS	601	-----	304	125.61	152	147.07	295.30	222.65	5023	4514.33	1632.25	6146.58

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
113	37	2	0	0	0	0	0

continued

Table 1.—Yields of veneer and associated products from unthinned slash pine plantations (continued)

AGE: 26 SITE INDEX: 80 (25-YEAR BASIS) NUMBER OF SURVIVING TREES: 600

STAND STRUCTURE			PRODUCTS FROM VENEER PORTION						PRODUCTS FROM PULPWOOD PORTION			
D.B.H. CLASS	TREES	MEAN TREE HEIGHT	STUDS	STUD VOLUME	VENEER BOLTS	NET VENEER VOLUME	CHIP VOLUME	BARK VOLUME	PULPWOOD BOLTS	WOOD VOLUME	BARK VOLUME	TOTAL VOLUME
INCHES	NUMBER	FEET	NUMBER	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.	NUMBER	CU. FT.	CU. FT.	CU. FT.
1												
2												
3	3	49.1	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
4	16	59.5	0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0
5	42	66.7	0	0.0	0	0.0	0.0	0.0	126	56.30	29.28	85.57
6	73	72.0	0	0.0	0	0.0	0.0	0.0	438	255.76	107.92	363.67
7	102	76.1	0	0.0	0	0.0	0.0	0.0	918	604.80	236.66	841.46
8	117	79.3	0	0.0	0	0.0	0.0	0.0	1170	1011.84	376.26	1388.10
9	114	81.8	0	0.0	0	0.0	0.0	0.0	1254	1341.45	478.44	1819.89
10	87	83.9	174	71.90	87	67.41	167.23	127.46	870	1026.74	331.45	1358.19
11	42	85.7	168	69.42	84	98.15	163.92	123.38	378	480.59	147.62	628.22
12	5	87.2	30	12.40	15	23.98	30.20	22.81	40	52.47	15.85	68.32
13												
14												
15												
TOTALS	601	-----	372	153.71	186	189.54	361.36	273.65	5194	4829.93	1723.47	6553.40

NUMBER OF VENEER BOLTS BY BOLT DIAMETER CLASS

8	9	10	11	12	13	14	15
129	52	5	0	0	0	0	0

PART II--DEVELOPMENT OF THE MODEL

Bennett and Swindel's (1972) taper model was modified to extend it below breast height and to increase its flexibility for upper-stem predictions.

Let:

h = height above ground,

h_s = average stump height,

D = diameter at breast height,

H = total tree height,

and

dia(h) = a general mathematical expression for the expected diameter (either inside bark or outside bark) as a function of height (h) above the ground.

In this work different expressions for dia(h) are used for $h \leq 4.5$ and $h \geq 4.5$, but the taper model is constructed so the two segments come together at breast height. That is,

$$\text{dia}(4.5) = f_D, \tag{1}$$

where f_D is a function of the breast-high diameter. The choice of the function f_D (specific choices given later) determines whether the model is for inside-bark or outside-bark diameters.

The lower-stem model is obtained by constraining the expression

$$\text{dia}(h) = \eta_0 h^{\eta_1}, \quad h_s \leq h \leq 4.5, \tag{2}$$

such that

$$\eta_0 (4.5)^{\eta_1} = f_D, \tag{3}$$

which when solved for the parameter η_0 and substituted back to Equation 2, yields

$$\text{dia}(h) = f_D\left(\frac{h}{4.5}\right)^{\eta_1}, \quad h_s \leq h \leq 4.5\ . \tag{4}$$

We chose the upper-stem segment expression as

$$\text{dia}(h) = \alpha_1\left(\frac{H-h}{H}\right) + \alpha_2\left(\frac{H-h}{H}\right)^2 + \alpha_3\left(\frac{H-h}{H}\right)^3, \quad 4.5 \leq h \leq H, \tag{5}$$

which has the property

$$\text{dia}(H) = 0, \tag{6}$$

that is, diameter at the top of the tree equals zero. Constraining Equation 5 similarly to Equation 3 produces the constrained upper-stem model

$$\text{dia}(h) = f_D\left(\frac{H-h}{H-4.5}\right) - \alpha_2 \frac{(H-h)(h-4.5)}{H^2}$$

$$- \alpha_3 \frac{(H-h)(h-4.5)(2H-h-4.5)}{H^3}, \quad 4.5 \le h \le H \ . \tag{7}$$

Model flexibility was increased by setting

$$- \alpha_2 = g(f_D), \tag{8}$$

yielding the general upper-stem expression

$$\text{dia}(h) = f_D\left(\frac{H-h}{H-4.5}\right) + g(f_D) \frac{(H-h)(h-4.5)}{H^2}$$

$$- \alpha_3 \frac{(H-h)(h-4.5)(2H-h-4.5)}{H^3}, \quad 4.5 \le h \le H. \tag{9}$$

The outside-bark and inside-bark taper models are obtained from Equations 4 and 9 as follows. For the outside-bark model, choose

$$g(f_D) = \beta_{\Delta 1} + \beta_{\Delta 2} f_D + \beta_{\Delta 3} f_D^2 \ , \tag{10}$$

$$f_D = D \ , \tag{11}$$

and, for notational convenience,

$$- \alpha_3 = \beta_{\Delta 4} \ . \tag{12}$$

This results in the model

$$\Delta_h = \begin{cases} D\left(\frac{h}{4.5}\right)^{\eta_{\Delta 1}}, \quad h_s \le h \le 4.5 \ , & \text{(13a)} \\ \\ D\left(\frac{H-h}{H-4.5}\right) + \beta_{\Delta 1} \frac{(H-h)(h-4.5)}{H^2} + \beta_{\Delta 2} \frac{D(H-h)(h-4.5)}{H^2} & \end{cases}$$

$$+ \beta_{\Delta 3} \frac{D^2 (H-h)(h-4.5)}{H^2} + \beta_{\Delta 4} \frac{(H-h)(h-4.5)(2H-h-4.5)}{H^3}, \quad 4.5 \le h \le H \ . \tag{13b}$$

For the inside-bark model, choose the same relationships as for the outside-bark model, that is,

$$g(f_D) = \beta_{\delta 1} + \beta_{\delta 2} f_D + \beta_{\delta 4} f_D^2 \tag{14}$$

and

$$-\alpha_3 = \beta_{\delta 4} , \tag{15}$$

but choose

$$f_D = \gamma_{\delta 1} + \gamma_{\delta 2} D . \tag{16}$$

This results in the model

$$\delta_h = \begin{cases} (\gamma_{\delta 1} + \gamma_{\delta 2} D)\left(\frac{h}{4.5}\right)^{\eta_{\delta 1}} , \quad h_s \le h \le 4.5 , & (17a) \\ (\gamma_{\delta 1} + \gamma_{\delta 2} D)\left(\frac{H-h}{H-4.5}\right) + \beta_{\delta 1} \frac{(H-h)(h-4.5)}{H^2} \\ \quad + \beta_{\delta 2} (\gamma_{\delta 1} + \gamma_{\delta 2} D)\frac{(H-h)(h-4.5)}{H^2} \\ \quad + \beta_{\delta 3} (\gamma_{\delta 1} + \gamma_{\delta 2} D)^2 \frac{(H-h)(h-4.5)}{H^2} \\ \quad + \beta_{\delta 4} \frac{(H-h)(h-4.5)(2H-h-4.5)}{H^3} , \quad 4.5 \le h \le H . & (17b) \end{cases}$$

Lower-stem inside- and outside-bark diameters were measured at heights of 0.5, 2.0, 3.0, and 4.5 feet on 98 trees with diameters at breast height of 9.0 to 18.0 inches. No records were kept of the density regimes from which these 98 trees came; however, densities under normal stand conditions should not materially affect the shape of the lower-stem taper. Upper-stem measurements were made at 4-foot intervals on 288 trees with breast-high diameters of 3.7 to 18.0 inches. Care was taken to sample a range of heights in each diameter class and to sample trees from the naturally occurring density regimes.

The parameter $\eta_{\Delta 1}$ for the outside bark, lower-stem taper curve was estimated by least squares using the expression,

$$\ln(\Delta_h) - \ln(D) = \eta_{\Delta 1} \ln\left(\frac{h}{4.5}\right) + \epsilon_\ell \quad . \tag{18}$$

Estimates of the $\beta_{\Delta i}$'s for the outside bark, upper-stem taper curve were obtained by using least squares estimation with the model

$$\Delta_h - D\left(\frac{H-h}{H-4.5}\right) = \beta_{\Delta 1} \frac{(H-h)(h-4.5)}{H^2} + \beta_{\Delta 2} \frac{D(H-h)(h-4.5)}{H^2}$$

$$+ \beta_{\Delta 3} \frac{D^2 (H-h)(h-4.5)}{H^2}$$

$$+ \beta_{\Delta 4} \frac{(H-h)(h-4.5)(2H-h-4.5)}{H^3} + \epsilon_u \quad . \tag{19}$$

The estimates are:

$\hat{\eta}_{\Delta 1} = -0.1097,$

$\hat{\beta}_{\Delta 1} = 16.0719,$

$\hat{\beta}_{\Delta 2} = 0.676434,$

$\hat{\beta}_{\Delta 3} = 0.00516633,$

and

$\hat{\beta}_{\Delta 4} = -11.7321.$

Parameter estimates for the inside-bark taper model were obtained in two steps. First, $\gamma_{\delta 1}$ and $\gamma_{\delta 2}$ were estimated by fitting the model

$$\delta_{4.5} = \gamma_{\delta 1} + \gamma_{\delta 2} D + \xi \tag{20}$$

to the measured breast-high diameters inside bark ($\delta_{4.5}$) and outside bark (D). Second, the resulting estimates ($\hat{\gamma}_{\delta 1}$ and $\hat{\gamma}_{\delta 2}$) were substituted and then $\eta_{\delta 1}$ and the $\beta_{\delta i}$'s were estimated in the same way as the outside-bark parameters. The estimates are:

$\hat{\gamma}_{\delta 1} = -0.484970,$

$\hat{\gamma}_{\delta 2} = 0.887077,$

$\hat{\eta}_{\delta 1} = -0.1050,$

$\hat{\beta}_{\delta 1} = 8.21592,$

$$\hat{\beta}_{\delta 2} = 0.676338,$$

$$\hat{\beta}_{\delta 3} = 0.0100534,$$

and

$$\hat{\beta}_{\delta 4} = -5.65717.$$

The above estimation approach was used instead of nonlinear methodology, because the computations were easier and we were primarily interested in unbiasedness of the estimators. The following statistics of fit were obtained:

	Equation number			
	13a	13b	17a	17b
Square root of mean square error	0.47	0.42	0.54	0.41
Coefficient of determination	0.981	0.986	0.967	0.983

Total cubic-foot volume inside or outside bark for a stem section between heights h_ℓ and h_u ($h_\ell < h_u$) is estimated from the volume of the geometric form obtained by revolving one-half the taper curve between h_ℓ and h_u around the h-axis. Given the taper curve dia(h), this volume of revolution is

$$V = \int_{h_\ell}^{h_u} \pi \left[\frac{\text{dia}(h)}{2(12)}\right]^2 dh \,. \tag{21}$$

The resulting volume predictor for the outside-bark taper curve is

$$V_{h_\ell}^{h_u} = \begin{cases} \dfrac{\pi(4.5)^{-2\hat{\eta}_{\Delta 1}}}{576(2\hat{\eta}_{\Delta 1}+1)} D^2 \left(h_u^{2\hat{\eta}_{\Delta 1}+1} - h_\ell^{2\hat{\eta}_{\Delta 1}+1} \right), & h_s \le h_\ell < h_u \le 4.5, \end{cases} \tag{22a}$$

$$\begin{aligned} & \frac{\pi}{576} \Big[R_{\Delta 0}^2 (h_u - h_\ell) + R_{\Delta 0} R_{\Delta 1} (h_u^2 - h_\ell^2) \\ & + \frac{1}{3} (R_{\Delta 1}^2 + 2R_{\Delta 0} R_{\Delta 2}) (h_u^3 - h_\ell^3) + \frac{1}{2} (R_{\Delta 0} R_{\Delta 3} + R_{\Delta 1} R_{\Delta 2}) (h_u^4 - h_\ell^4) \\ & + \frac{1}{5} (R_{\Delta 2}^2 + 2R_{\Delta 1} R_{\Delta 3}) (h_u^5 - h_\ell^5) + \frac{1}{3} R_{\Delta 2} R_{\Delta 3} (h_u^6 - h_\ell^6) \\ & + \frac{1}{7} R_{\Delta 3}^2 (h_u^7 - h_\ell^7) \Big], \quad 4.5 \le h_\ell < h_u \le H, \end{aligned} \tag{22b}$$

where

$$R_{\Delta 0} = \frac{DH}{H-4.5} - \frac{(4.5\hat{\beta}_{\Delta 1} + 9\hat{\beta}_{\Delta 4})}{H} - \frac{4.5\hat{\beta}_{\Delta 2}D}{H} - \frac{4.5\hat{\beta}_{\Delta 3}D^2}{H}$$

$$+ \frac{20.25\hat{\beta}_{\Delta 4}}{H^2} , \tag{23}$$

$$R_{\Delta 1} = - \frac{D}{H-4.5} + \frac{(\hat{\beta}_{\Delta 1} + 2\hat{\beta}_{\Delta 4})}{H} + \frac{\hat{\beta}_{\Delta 2}D}{H} + \frac{(4.5\hat{\beta}_{\Delta 1} + 9\hat{\beta}_{\Delta 4})}{H^2}$$

$$+ \frac{4.5\hat{\beta}_{\Delta 2}D}{H^2} + \frac{\hat{\beta}_{\Delta 3}D^2}{H} + \frac{4.5\hat{\beta}_{\Delta 3}D^2}{H^2} - \frac{20.25\hat{\beta}_{\Delta 4}}{H^3} , \tag{24}$$

$$R_{\Delta 2} = - \frac{(\hat{\beta}_{\Delta 1} + 3\hat{\beta}_{\Delta 4})}{H^2} - \frac{\hat{\beta}_{\Delta 2}D}{H^2} - \frac{\hat{\beta}_{\Delta 3}D^2}{H^2} , \tag{25}$$

$$R_{\Delta 3} = \frac{\hat{\beta}_{\Delta 4}}{H^3} . \tag{26}$$

The volume predictor for the inside-bark taper curve is

$$\hat{V}_{h_\ell}^{h_u} = \begin{cases} \dfrac{\pi(\hat{\gamma}_{\delta 1} + \hat{\gamma}_{\delta 2}D)^2}{576(4.5)^{2\hat{\eta}_{\delta 1}}(2\hat{\eta}_{\delta 1}+1)} \left(h_u^{2\hat{\eta}_{\delta 1}+1} - h_\ell^{2\hat{\eta}_{\delta 1}+1} \right) , & h_s \le h_\ell < h_u \le 4.5, \quad (27a) \\ \dfrac{\pi}{576} \left[R_{\delta 0}^2 (h_u - h_\ell) + R_{\delta 0} R_{\delta 1} (h_u^2 - h_\ell^2) \right. & \end{cases}$$

$$+ \frac{1}{3}(R_{\delta 1}^2 + 2R_{\delta 0} R_{\delta 2})(h_u^3 - h_\ell^3) + \frac{1}{2}(R_{\delta 0}R_{\delta 3} + R_{\delta 1} R_{\delta 2})(h_u^4 - h_\ell^4)$$

$$+ \frac{1}{5}(R_{\delta 2}^2 + 2R_{\delta 1}R_{\delta 3})(h_u^5 - h_\ell^5) + \frac{1}{3} R_{\delta 2} R_{\delta 3}(h_u^6 - h_\ell^6)$$

$$\left. + \frac{1}{7} R_{\delta 3}^2 (h_u^7 - h_\ell^7) \right] , \quad 4.5 \le h_\ell < h_u \le H, \tag{27b}$$

where

$$R_{\delta 0} = \frac{(\hat{\gamma}_{\delta 1} + \hat{\gamma}_{\delta 2} D)H}{H-4.5} - \frac{(4.5\hat{\beta}_{\delta 1} + 4.5 \hat{\gamma}_{\delta 1} \hat{\beta}_{\delta 2} + 4.5 \hat{\gamma}_{\delta 1}^2 \hat{\beta}_{\delta 3} + 9\hat{\beta}_{\delta 4})}{H}$$

$$+ \frac{20.25\hat{\beta}_{\delta 4}}{H^2} - \frac{(4.5 \hat{\gamma}_{\delta 2}\hat{\beta}_{\delta 2} + 9 \hat{\gamma}_{\delta 1}\hat{\gamma}_{\delta 2} \hat{\beta}_{\delta 3})D}{H} - \frac{4.5 \hat{\gamma}_{\delta 2}^2 \hat{\beta}_{\delta 3} D^2}{H}, \quad (28)$$

$$R_{\delta 1} = - \frac{(\hat{\gamma}_{\delta 1} + \hat{\gamma}_{\delta 2} D)}{H-4.5} + \frac{(\hat{\beta}_{\delta 1} + \hat{\gamma}_{\delta 1}\hat{\beta}_{\delta 2} + \hat{\gamma}_{\delta 1}^2\hat{\beta}_{\delta 3} + 2\hat{\beta}_{\delta 4})}{H}$$

$$+ \frac{(4.5\hat{\beta}_{\delta 1} + 4.5 \hat{\gamma}_{\delta 1}\hat{\beta}_{\delta 2} + 4.5 \hat{\gamma}_{\delta 1}^2 \hat{\beta}_{\delta 3} + 9 \hat{\beta}_{\delta 4})}{H^2}$$

$$+ \frac{(\hat{\gamma}_{\delta 2}\hat{\beta}_{\delta 2} + 2\hat{\gamma}_{\delta 1}\hat{\gamma}_{\delta 2}\hat{\beta}_{\delta 3})D}{H} + \frac{(4.5 \hat{\gamma}_{\delta 2}\hat{\beta}_{\delta 2} + 9 \hat{\gamma}_{\delta 1}\hat{\gamma}_{\delta 2}\hat{\beta}_{\delta 3})D}{H^2}$$

$$+ \frac{\hat{\gamma}_{\delta 2}^2 \hat{\beta}_{\delta 3} D^2}{H} + \frac{4.5 \hat{\gamma}_{\delta 2}^2 \hat{\beta}_{\delta 3} D^2}{H^2} - \frac{20.25\hat{\beta}_{\delta 4}}{H^3}, \quad (29)$$

$$R_{\delta 2} = - \frac{(\hat{\beta}_{\delta 1} + \hat{\gamma}_{\delta 1}\hat{\beta}_{\delta 2} + \hat{\gamma}_{\delta 1}^2\hat{\beta}_{\delta 3} + 3\hat{\beta}_{\delta 4})}{H^2} - \frac{(\hat{\gamma}_{\delta 2}\hat{\beta}_{\delta 2} + 2\hat{\gamma}_{\delta 1}\hat{\gamma}_{\delta 2}\hat{\beta}_{\delta 3})D}{H^2}$$

$$- \frac{\hat{\gamma}_{\delta 2}^2 \hat{\beta}_{\delta 3} D^2}{H^2}, \quad (30)$$

$$R_{\delta 3} = \frac{\hat{\beta}_{\delta 4}}{H^3}. \quad (31)$$

The stand table predictor (Clutter and Shephard 1968) uses site index (S) for index age 25, stand age (A), and the number of surviving trees per acre (N) at age A to estimate the number of trees for the diameter class (d_ℓ, d_u). The predicted frequency is

$$f(d_\ell, d_u) = \frac{\Gamma(\alpha + \beta + 2)}{\Gamma(\alpha + 1)\,\Gamma(\beta + 1)} \int_{x_\ell}^{x_u} x^{\alpha} (1 - x)^{\beta} dx \qquad (32)$$

where $\Gamma(\cdot)$ is the gamma function,

$$\alpha = 2.63938, \qquad (33)$$

$$\beta = 1.07118 + 0.02463\,(N/A), \qquad (34)$$

$$x_\ell = \frac{d_\ell - D_{min}}{D_{max} - D_{min}}, \qquad (35)$$

$$x_u = \frac{d_u - D_{min}}{D_{max} - D_{min}}, \qquad (36)$$

$$D_{min} = 1.58549 - 3.50521 \log_{10}(N) + 5.46330 \log_{10}(S), \qquad (37)$$

and

$$D_{max} = 2.79363 - 6.33124 \log_{10}(N) + 15.39256 \log_{10}(S) + 0.05077\,(N/A) - 48.46639 \frac{\log_{10}(S)}{A} \qquad (38)$$

Numerical integration was used to compute $f(d_\ell, d_u)$.

The total height predictor is

$$\log_{10}(H) = 1.64770 + 0.0062576(S) + 0.009697\,(N/100) - 4.75103/A - 0.998175/D \; . \qquad (39)$$

The average taper curve for the diameter class (d_ℓ, d_u) is specified by substituting diameter

$$D_m = \frac{d_\ell + d_u}{2}$$

and total height from Equation (39) into the above specified taper models and volume equations.

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Mixed yields of veneer, pulpwood, studs (from veneer cores), and chips are predicted for unthinned, old-field plantations of slash pine in the south Georgia and north Florida flatwoods. Stand area, stand age, an estimate of site index, and the present number of trees per acre are required to make predictions.

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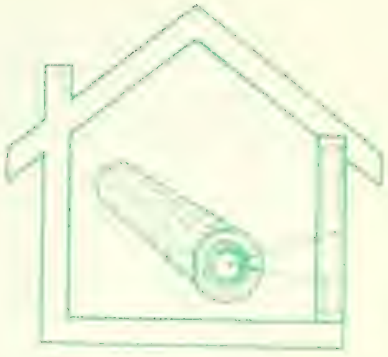

COM-PLY 10 REPORT

DEMONSTRATION HOUSES BUILT WITH COM-PLY PRODUCTS

AMERICAN PLYWOOD ASSOCIATION

COOPERATIVE RESEARCH

DEMONSTRATION HOUSES BUILT WITH COM-PLY PRODUCTS

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and Standards

PREFACE

This report is one of a series on the possibilities of producing house framing and structural panels with particleboard cores and veneer facings. These COM-PLY or composite materials were designed to be used interchangeably with conventional lumber and plywood in homes. Research on structural framing is presently limited to COM-PLY studs but will be extended to include larger members such as floor joists.

In 1973, the home-building industry faced a shortage of lumber and plywood and consequent rising prices. Both industry and government recognized that this situation was not a temporary problem, and that long-range plans for better using the Nation's available forest resources would be necessary.

The USDA Forest Service and the U.S. Department of Housing and Urban Development accelerated cooperative research on ways to utilize the whole tree. They concentrated on composite wood products made with particleboard and veneer as a way of using not only more of the tree stem, but also using less desirable trees and a greater variety of tree species than would conventional wood products. The particleboard which comprises a large portion of the COM-PLY stud is made from ground-up wood that comes from forest residues, mill residues, or low-quality timber. Thus, such composites could greatly increase the amount of lumber and plywood available for residential construction, our major use of wood, without eroding the Nation's timber supply.

Research on composite wall framing was performed by the Wood Products Research Unit, Southeastern Forest Experiment Station, Athens, Georgia. The American Plywood Association cooperated in these studies by designing and testing composite panel products that are interchangeable with plywood. Both types of products have been incorporated in demonstration houses through HUD's Experimental Housing Program.

Included in this series will be reports on structural properties, durability, dimensional stability, strength, and stiffness of composite studs. Other reports will describe the overall project, compare the strength of composite and solid wood studs, suggest performance standards for composite studs, and provide construction details on houses incorporating such studs. Still others will explore the economic feasibility of manufacturing composite studs and panels and estimate the amount and quality of veneer available from southern pines. These reports, called the COM-PLY series, will be available from the Southeastern Forest Experiment Station and the U.S. Department of Housing and Urban Development.

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DEMONSTRATION HOUSES BUILT WITH COM-PLY PRODUCTS

Abstract.--Composite studs and panels developed in the laboratory were used to build six demonstration houses in all kinds of weather. Builders found they could cut, nail, and install the composite products just like lumber studs and plywood. Composite products proved to be adaptable to various uses. Builders liked the straightness of composite studs because this quality resulted in straighter walls, tighter joints, and less waste on the job site. Carpenters generally felt composite panels were stiffer than the plywood they were accustomed to. The houses were built under the Experimental Housing Program of the Department of Housing and Urban Development.

KEYWORDS: Plywood, composite studs and panels, sheathing, flooring, siding, framing, experimental housing.

The Forest Service, the U.S. Department of Housing and Urban Development (HUD), and the American Plywood Association (APA) have developed two new wood products for home building. Both are composite products. COM-PLY studs are designed for framing the walls of houses (fig. 1); COM-PLY panels are designed for sheathing the roofs and floors of houses (fig. 2).

Figure 1.--A COM-PLY 2 x 4 stud.

Wood framing and sheathing are used in most single-family and garden-apartment housing in the United States. With the composite concept, only half the trees used by conventional sawing methods are needed to manufacture a given amount of

lumber and plywood, a reduction that will allow our diminishing forest resources to stretch much further. The new composite products have been designed and thoroughly tested in the laboratory, but the real test is to use them in homes. The Forest Service and APA have now successfully demonstrated that the two composite products can be used for this purpose.

Figure 2.--Corner view of a COM-PLY panel.

This report describes the building of the demonstration houses, the composite products used, and the reactions of the people involved.

HUD'S EXPERIMENTAL HOUSING PROGRAM

The demonstration houses were made available through HUD's Experimental Housing Program as authorized under Section 233 of the National Housing Act of 1961. The program was conceived to encourage the development of new designs, materials, and techniques in housing construction. Under the program, mortgages may be insured by HUD on properties that incorporate new or untried construction concepts aimed at reducing housing costs, raising living standards, or improving neighborhood design. Research funds are used to improve materials and components for residential units and to demonstrate their use under actual or simulated field conditions (fig. 3). The Experimental Housing Program allows builders to try new or advanced technologies not yet recognized in HUD's Minimum Property Standards.

It is difficult to evaluate a new material or system without having seen it in use. Laboratory tests never tell the final story. New materials must be shipped, stored, sawed, installed, and used before an evaluation is valid. In the case of COM-PLY products, it was necessary to use them in both prefabricated and conventional houses. The prefabricator could evaluate ease of handling in the plant, fitting in the jigs, power nailing, and factory gluing. Carpenters at the building site could evaluate ease of sawing, nailing, gluing at the site, and lifting into position. The builder could reveal any problems created by storing the material outdoors in bad weather and the attitudes of the building crew and the local inspector.

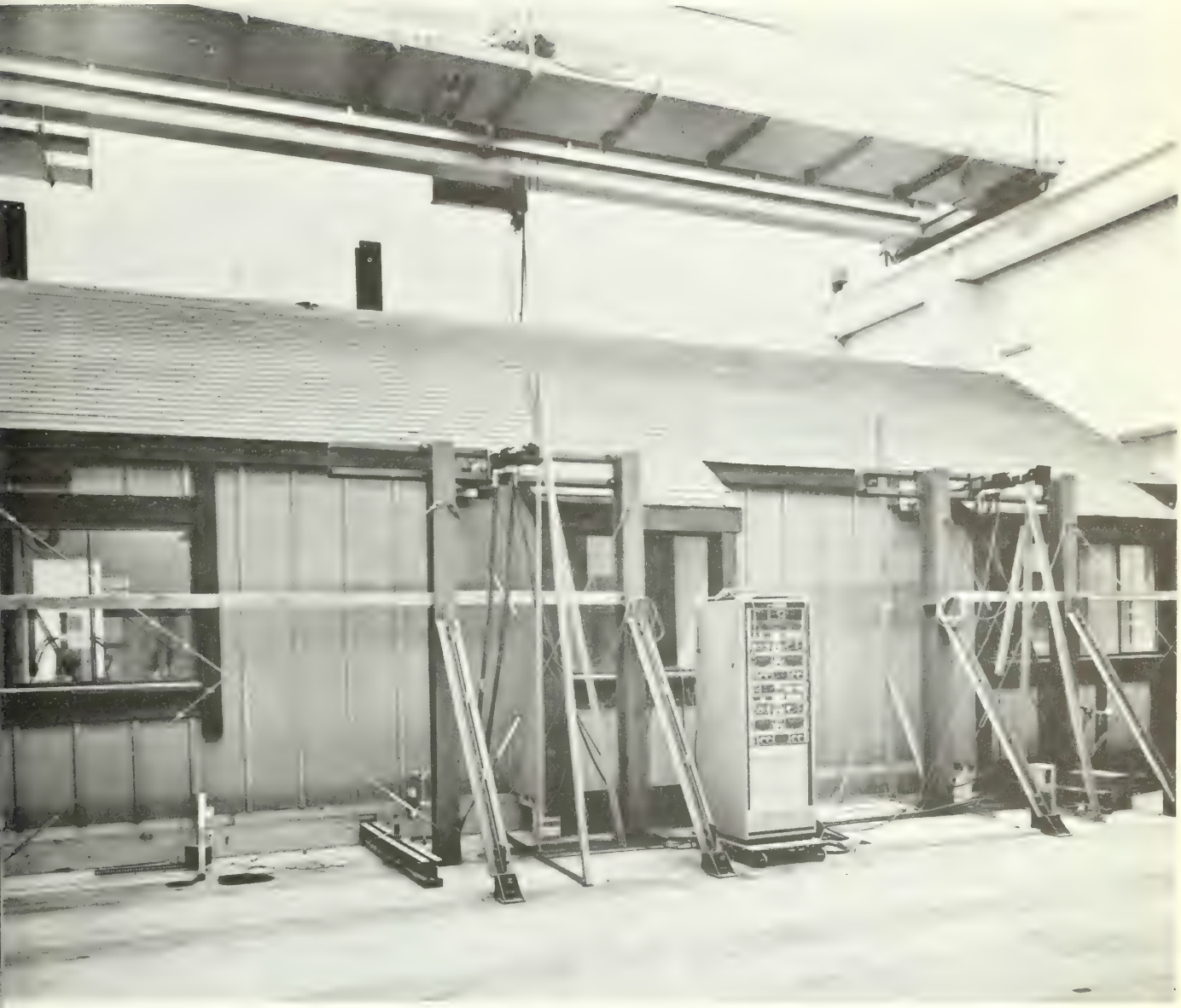

Figure 3.--Full-scale structural test of house being performed for HUD in the National Bureau of Standards Research Laboratory. Final test for research houses is in the field.

The demonstrations have also drawn public attention to the COM-PLY program. The houses were publicized and opened for display during construction. Such demonstrations serve to inform potential homeowners of the new technologies under development.

DEMONSTRATION HOUSE NO. 1

Late in 1974, Ryland Homes of Columbia, Maryland, built the United States' first demonstration house incorporating COM-PLY studs. The house was located in the Riverdale Subdivision of Severna Park, Maryland, near Annapolis.

SHOP FABRICATION WITH COM-PLY STUDS

When a shipment of 400 COM-PLY studs arrived at the Ryland Homes factory, they were stored outdoors without protection. Some were stacked on end and leaned against stored lumber; others were placed directly on pavement or on top of lumber piles.

Product Engineering Manager Joe Drobney explained that conventional studs sometimes warp after a few days' exposure to weathering and become unusable. Plant and Processing Manager Walley Borger pointed out that Ryland Homes had ceased using studs made from veneer cores and conventional 2 x 3 partition studs because they were not straight and strong enough. He indicated that his firm would be willing to pay more for COM-PLY studs if they would overcome these problems.

On November 18, Ryland Homes fabricated the exterior walls and interior partitions for the demonstration house (fig. 4). Cutting, nailing, and assembling the COM-PLY studs into wall panels moved smoothly on the production line. The straightness of COM-PLY studs proved to have many advantages for shop fabrication. Workers saved time because crooked studs did not have to be sorted out and cut into shorter lengths for use as blocking, sills, or cripples. When wood siding was being automatically machine-nailed to the stud framing, the straight COM-PLY studs gave greater assurance that the siding staples had a solid stud surface to hit. Wherever the siding was routed out for a window opening, COM-PLY studs provided a more accurate rectangular opening, according to the workmen. An accurate fit is important, especially when one wall panel joins with another and at corners (fig. 5). A poor fit at these points could cause a bad joint in on-site construction. In turn, this bad joint could cause a costly repair at the job site or lower the quality of construction.

End-nailing panel studs with power nailers was as easy as conventional nailing, and no end splits occurred. However, nailing into the 3-1/2-inch width of COM-PLY studs required greater force than when sawn lumber was used. Double studs for window and door openings and studs with blocking between them for corners were assembled by side-nailing. The air pressure on the nailing machine at these subassembly stations had to be increased slightly for COM-PLY studs.

The workmen noticed that the new studs were heavier than the white fir and spruce studs they were used to. Drobney thought the increased weight could be a disadvantage for wall panels that had to be lifted to the upper floor of two-story houses.

For shop fabrications, the Ryland staff felt that COM-PLY studs had advantages over conventional sawn studs. They agreed that they would prefer purchasing COM-PLY studs for production and would be willing to pay more for them.

FINISHING THE HOUSE

All house components were delivered on a flat-bed truck and dumped at the job site, where they were directly exposed to intermittent rain and snow. A few panels were set in mud puddles, and a few were covered by a pile of crushed stone during construction.

A subcontractor built the 1,470-square-foot, two-story house by his usual methods. Although the subcontractor did not mention it, the workmen found that

more force was required to side-nail COM-PLY studs together at panel joints than when studs of sawn lumber were used. Nailing COM-PLY studs to plates at the floor and ceiling was no more difficult than with framing of sawn studs (fig. 6).

Figure 4.--Assembling a wall panel with COM-PLY studs in a factory.

Bracing was attached to COM-PLY studs with 16d common nails. Occasionally, a small piece of particleboard about the size of a 50-cent piece popped out when the point of the bracing nail penetrated completely through the stud (fig. 7). Even though this spalling did not affect the stud's strength, the appearance was objectionable. Of course, the wall covering eventually hid such areas.

The carpenters said that interior partition panels made with COM-PLY studs withstood handling in the field better than those with studs of sawn lumber. With COM-PLY studs, there was less tendency for joints between plates and studs to come apart during erection.

Figure 5.--Two wall panels made with COM-PLY studs join snugly at a corner.

Freezing rain and snow halted work for one day. However, this bad weather did not affect strength or dimensional stability of the COM-PLY studs.

During construction, the house was featured on national TV news and inspected by officials with the local building code. John R. McGuire, Chief of the Forest Service, Michael H. Moskow, assistant secretary for policy development and research at HUD, and numerous officials from wood-related trade associations around Washington D.C., inspected the house (fig. 8). The house was subsequently sold and occupied.

Figure 6.--COM-PLY studs nailed to floor and top plates.

Figure 9.--Demonstration house incorporating composite studs in Aurora, Illinois.

This house was built stud by stud and involved more toe-nailing than a factory-built home. The carpenters found they had to start driving toe nails a full inch from the end of the stud to prevent cracking or breaking the stud's particleboard core.

One partition framed with COM-PLY studs was used to support kitchen cabinets. The builder followed his usual method of supporting cabinets by notching the studs on one side of the partition and inserting horizontal 2 x 4 cabinet supports (fig. 10). Such notching considerably weakens any stud, but it weakens COM-PLY studs more than solid wood studs. Although the wall covering, kitchen cabinets, and careful workmanship provided a satisfactory wall in this house, a warning against notching should be marked on the veneer face of COM-PLY studs during manufacture. There are ways to install cabinets without notching studs, and builders should be required to follow them.

Four to six inches of snow often covered the COM-PLY studs while they were stored at the site (fig. 11). In addition, the wall framing of the demonstration house was exposed to freezing rain and snow for several days before the roof was installed. This severe weather did not visibly deteriorate the COM-PLY studs.

Figure 10.--The builder notched COM-PLY studs to install kitchen cabinets.

Building this house demonstrated that carpenters could use the new studs for house framing essentially as they have used sawn studs for over a hundred years. The Dise house was visited by officials with the local building code, lumber retailers and manufacturers, and other interested persons in the Chicago area.

Figure 11.--Snow-covered COM-PLY studs at the building site.

DEMONSTRATION HOUSE NO. 3

In late June 1975, approximately 300 people including plywood manufacturers, wood-product scientists, building code officials, and news reporters visited the third demonstration house incorporating composite products. These people had come from all parts of the Nation to see the first house built with composite roof sheathing, floor sheathing, siding, and stud framing.

The 2,320-square-foot, two-story house was constructed during April, May, and early June 1975 (fig. 12). It was built on lot 15 in Heathwood II Subdivision at

the corner of N.E. 7th Street and N.E. 145th Avenue in Vancouver, Washington, across the Columbia River from Portland, Oregon. Pruitt Construction Company of Vancouver, Washington, constructed the house; and HUD insured the mortgage under Section 233 of the National Housing Act. The Pruitt Construction Company built the house piece by piece and completed it in 2 months, amid intermittent periods of heavy rain and hot, dry weather.

Figure 12.--The first demonstration house built with composite roof sheathing, floor sheathing, siding, and stud framing.

INSTALLATION OF COMPOSITE STUDS

Composite studs for this house were supplied by U.S. Plywood and Georgia Pacific Corporation. It proved as easy to cut, nail, and install walls and partitions with these COM-PLY studs as with conventional studs. The builder was especially pleased with the straightness of COM-PLY studs and said that they had a distinct advantage over conventional ones. The plumbers used right-angle drills to bore holes as large as 2-1/2 inches in diameter through the cores of the studs. These holes accommodated short, horizontal runs in the plumbing and electrical wiring. Laboratory tests at Athens, Georgia, had previously shown that such large

holes could be bored through COM-PLY studs without an appreciable loss of strength and stiffness (Wittenberg, in press). The house built by Pruitt Construction Company confirmed this finding.

The ends of the studs occasionally split when end nails were driven too close to the edges of the particleboard cores. The builder took Forest Service representatives through an uncompleted house built with conventional studs of sawn lumber and pointed out the end splits and crooked studs. He emphasized that these defects far outnumbered those in the COM-PLY studs used in the demonstration house. COM-PLY studs were used for blocking at a stairwell in the demonstration house. This blocking was cut on a 45° angle at each end and toe-nailed into place (fig. 13). No splitting occurred in the extensive toe-nailing used in the demonstration house, and the carpenters were pleased with the performance of the COM-PLY studs.

Figure 13.--COM-PLY studs used for blocking at a stairwell.

INSTALLATION OF COMPOSITE SHEATHING AND SIDING

Three major manufacturers of forest products cooperated in supplying the composite panels for the third demonstration house. Combination subflooring and underlayment was supplied by Potlatch Corporation; roof sheathing by Weyerhaeuser Company; and combination sheathing and siding by Evans Products Company.

Prior to construction, production panels typical of those used in the demonstration house were evaluated by laboratory tests. Included were an evaluation of glueline quality in the roof sheathing and floor underlayment and evaluations of structural and dimensional stability in the roof sheathing, underlayment, and siding. The roof sheathing and underlayment carried the American Plywood Association's (APA) grade-trademark, signifying that they had qualified under glue-bond testing as "APA Special-Use Panels."

The 7/16-inch-thick roof sheathing, made by Weyerhaeuser, consisted of a 1/4-inch particleboard core and a 1/10-inch face and back veneers of Douglas-fir. The core was made in Weyerhaeuser's particleboard plant in Marshfield, Wisconsin, with nonoriented flakes and a phenolic-resin binder.

The floors on the first and second stories consisted of a 5/8-inch, tongue-and-groove, single-layer floor system. The panels, produced by Potlatch Corporation, had a core of 3/8-inch oriented particleboard overlaid with 1/8-inch face and back veneers of Douglas-fir. The panels were tongued and grooved along the long edges.

The siding for the demonstration house was 5/8 inch thick with a reverse board-and-batten pattern. The panels were produced by Evans Products Company; the cores of these panels were produced by Potlatch Corporation from oriented wood particles. This particleboard core was made in a single step and consisted of a three-layered mat of wood particles bonded with phenolic resin. Evans Products Company overlaid the core with 1/8-inch face and back veneers of cedar. The panels were then milled with a rough-sawn surface and a reverse board-and-batten pattern, with grooves spaced 12 inches on center (fig. 14). The edges of the panels were shiplapped.

Figure 14.--Panels of rough-sawn siding with a reverse board-and-batten pattern and grooves spaced 12 inches on center.

The three types of composite panels were shipped directly to the contractor. APA, HUD, and Forest Service staff members observed, and at times participated in, the installation of the composite panels. Figures 15 through 19 illustrate the construction process.

The first composite panels to go into place were the floor underlayment (fig. 15). They were attached to the floor joists with nails spaced 12 inches on center and construction adhesive (fig. 16). During installation, adhesive was also applied to the tongue-and-groove joints of the panels (fig. 17).

Figure 15.--Laying the composite floor panels. Note the tongue-and-groove joints.

The carpenters found that the composite panels could be handled and installed as easily as regular plywood panels. The tongue-and-groove joints fitted properly and went into place easily. Nails were as easy to drive through the composite panels as through regular plywood.

The siding panels were installed next. They were attached to the wall framing while in a horizontal position, as shown in figure 18. After assembly on the deck, the walls were tilted into place with wall jacks (fig. 19). The wall framing consisted of regular 2 x 4 lumber plates and COM-PLY studs. All studs were spaced 16 inches on center, and the siding panels were attached directly to the framing. The builder used no wall sheathing or exterior wall bracing. All panels were nailed to the wall framing with 8d galvanized box nails spaced 6 inches on center around the perimeter of the panel and 12 inches on center at intermediate studs.

The last panels to go in place were the roof sheathing. Because this house had a gambrel roof, the 7/16-inch panels were used for both roof sheathing and the combined wall and roof surfaces of the second story. The panels used on the steep

portion of the roof were attached to the framing while in a horizontal position, and the studs were spaced 16 inches on center. The walls were then tilted into place and the roof trusses installed. The remaining roof sheathing was then installed on trusses spaced 24 inches on center.

Figure 16.--Applying construction adhesive to the joists.

Laboratory tests indicated that metal clips and wood blocking were unnecessary at adjacent edges of the sheathing. The roof sheathing was attached to the framing with pneumatically driven staples spaced 6 inches on center at the perimeter and 12 inches on center at intermediate supports (fig. 20).

On the steep portion of the gambrel roof, commercially pre-assembled panels of cedar shingles were attached according to the manufacturer's recommendations. On the flatter portion, regular cedar shingles were attached according to normal construction procedures.

No problems were encountered during the installation of any of the three types of composite panels. All panels went into place easily, just as though they were made entirely of veneer. When interviewed, the carpentry superintendent was enthusiastic about the new panels. The builder was also satisfied with the panels and expressed a willingness to use them again. Such panels could be used interchangeably with regular plywood panels, which have long been accepted in residential and commercial construction.

Figure 17.--Applying adhesive to the tongue-and-groove joints of a panel.

Figure 18.--Attaching the siding panels to the framing.

Figure 19.--Raising a wall panel into place.

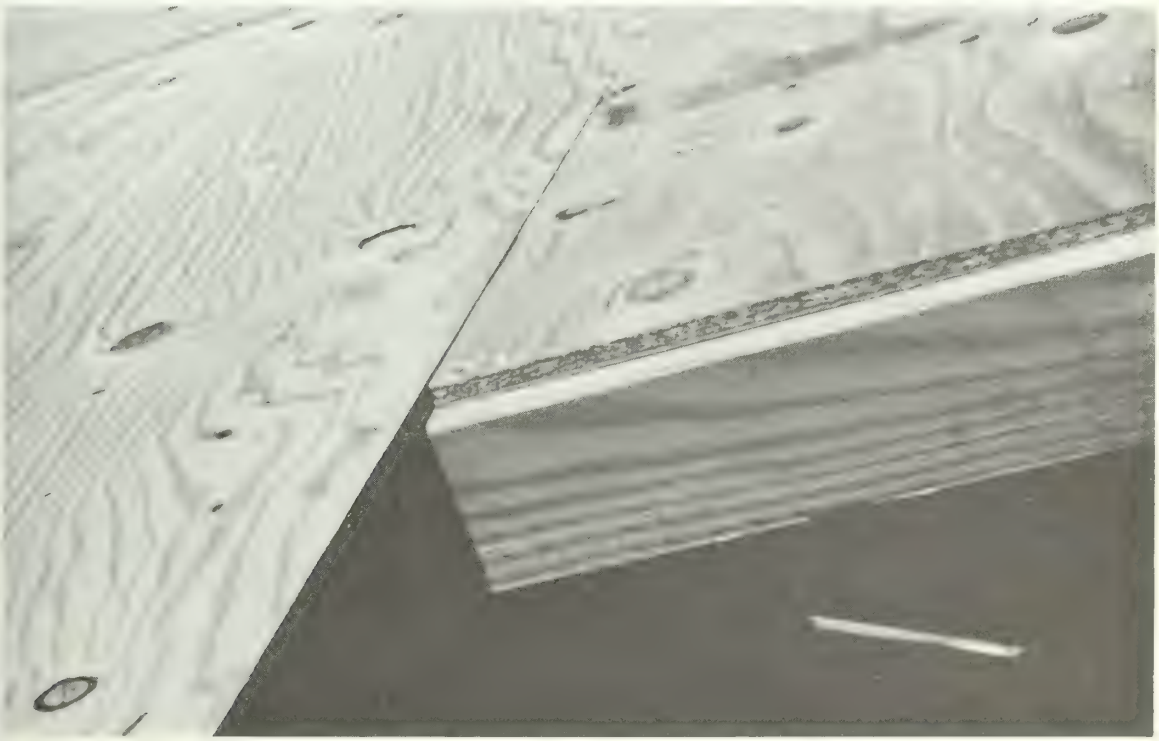

Figure 20.--Roof sheathing in position for stapling to the rafters.

Although it rained before and during construction, the tongue-and-groove joints went together easily, indicating that the new panels will perform similarly to plywood even when wet. Rain also fell on the roof sheathing after it was installed. As a result, the panels expanded in width and length as regular plywood would. A few of the panels over two roof trusses buckled because fasteners had missed the framing for as much as 44 inches. Such buckling would not have occurred if the panels had been adequately nailed.

DEMONSTRATION HOUSE NO. 4

In late summer 1975, Kettler Brothers, Inc., of Gaithersburg, Maryland, built the fourth demonstration house incorporating composite products. The two-story house, containing 2,400 square feet of living space and a 460-square-foot, two-car garage, was located at 10 Masten Brook Court in the Fairidge Subdivision, Montgomery Village, Maryland, near Washington, D.C. Kettler Brothers started construction in August 1975.

The two types of composite panels used were both produced by the Potlatch Corporation. One type was 7/16-inch-thick roof sheathing that looked like ordinary C-D, exterior-grade plywood. It had 1/10-inch face and back veneers of Douglas-fir and was a direct substitute for the 1/2-inch-thick plywood normally used for roof sheathing by the builder. The other type was single-layer floor underlayment 3/4 inch thick. These panels had 1/8-inch-thick face and back veneers of Douglas-fi The long edges of the floor panels were tongued and grooved so that the edges joined firmly together. This was the first time composite floor panels 3/4 inch thick had been used within the United States.

The first panels to go into place were the floor underlayment. A construction adhesive conforming to Specification AFG-01 of the American Plywood Association (1974) and nails spaced 12 inches on center were used to fasten the panels to joists spaced 16 inches apart. The glue was applied to the joists but not to the tongue-and-groove joints. One of the carpenters noted that the panels were easy to cut and nail and that they fitted together easier than most plywood panels.

After the first-floor walls and joists were put into place, the second-floor joists were installed at a spacing of 24 inches on center, and 3/4-inch underlayment panels were attached to the joists. As in the first floor, the panels went into place easily and were glued to the framing.

The last step of construction was to apply the 7/16-inch roof sheathing. These panels were attached to trusses spaced 24 inches on center and nailed at 6 inches on center at the perimeter of the panels and 12 inches on center at intermediate supports. No clips or blocking were used with the 7/16-inch sheathing.

During construction, there were intermittent periods of rain followed by hot, dry weather. There were no problems in installing the composite roof or floor panels. The panels went into place just like plywood.

DEMONSTRATION HOUSE NO. 5

In mid-December 1975, Mr. Jack Bowles of Augusta, Georgia, built a demonstration house incorporating COM-PLY studs. The one-story, 1,144-square-foot house was located at 2308 Old Boston Chapel Road in the Cherry Hill Subdivision, Augusta, Georgia (fig. 21).

Figure 21.--The demonstration house in Augusta, Georgia.

A subcontractor framed the house at the site. The framing carpenters had no difficulty in cutting, nailing, and installing the COM-PLY studs (fig. 22). They were impressed by the straightness and uniformity of the new studs.

Figure 22.--Carpenter framing the walls.

The framing crew used COM-PLY studs for blocking, corner posts, window sills, window cripples (fig. 23), door heads (fig. 24), and other framing. There was no comment about the weight of the studs or about the difficulty of driving nails into the 3-1/2-inch-wide faces of the studs. Most of the framing was completed on December 15 under clear, sunny skies. Soon after, the house was deluged with 2-1/2 days of rain. As in the previously built houses, the COM-PLY studs showed their resistance to warpage. They remained straight and dimensionally stable during the 4 weeks after construction when the house was open for inspection.

Figure 23.--COM-PLY studs used for window cripples.

Figure 24.--COM-PLY studs used for door heads.

The plumbing and heating subcontractors notched the faces of some of the COM-PLY studs for plumbing and air-conditioning pipes (fig. 25). Only a few studs were notched, mostly in nonload-bearing partitions where structural strength was not critical. The notching was unnecessary because holes drilled through the stud cores would have worked just as well (fig. 26).

The house was visited by building code officials, home builders, lumber dealers, wood products manufacturers, and others from throughout the Southeastern United States. The project received press coverage by newspapers, TV, and trade journals.

Figure 25.--Composite studs notched for plumbing pipes.

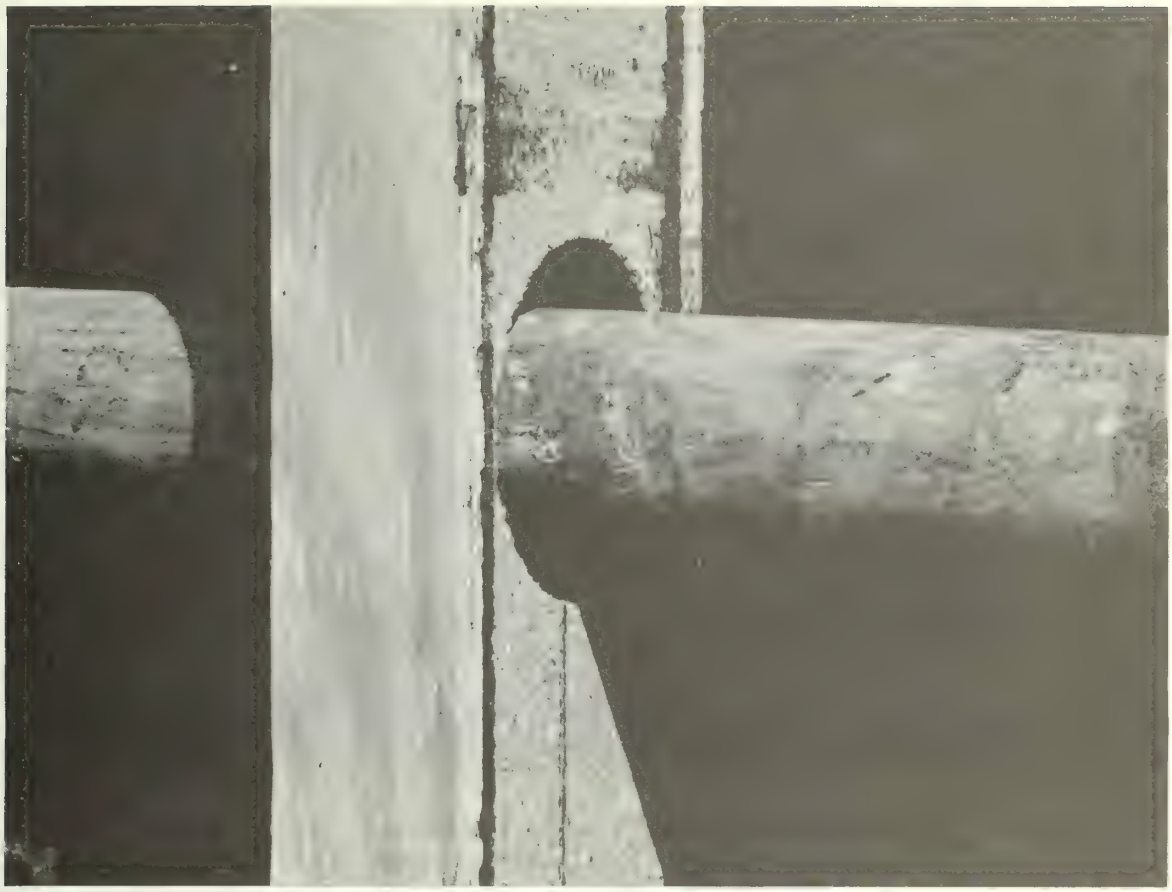

Figure 26.--Holes for plumbing pipes were drilled in the cores of COM-PLY studs.

DEMONSTRATION HOUSE NO. 6

In commemoration of the American Revolution Bicentennial, the National Aeronautics and Space Administration (NASA) started planning in early 1975 for the design and construction of a house to be ready for display at the Langley Research Center in Langley, Virginia. It was NASA's theory that the techniques and components developed for the aerospace program are applicable to the building industry.

The objectives of NASA's Project TECH house were to demonstrate the application of advanced technology and to help influence future development in home construction (fig. 27). Emphasis was placed on minimizing the requirement for energy and other utilities and integrating energy and water systems with building configuration and construction materials.

Studies were made of various components and methods believed to have a good chance of being cost-effective over the period of a typical home mortgage, assuming the generally accepted figure of a 10 percent increase in energy cost each year. Components chosen for the TECH house were those available to the building industry in 1976 or likely to be available before 1981.

The exterior walls of the house were framed with 2 x 6 wood studs so that they could be heavily insulated. COM-PLY studs were chosen for all interior partitions (fig. 28).

Figure 27.--NASA's Project TECH house at Langley Research Center in Langley, Virginia.

Figure 28.--COM-PLY studs were used to frame the interior partitions of NASA's Project TECH house. Large holes were drilled through the cores of the studs to accommodate plumbing.

The house was highly instrumented to allow for a detailed evaluation of its components during 1977. Recommendations will then be made about performance, cost-effectiveness, and interaction of the various systems.

CONCLUSIONS AND RECOMMENDATIONS

All builders interviewed were impressed with the straightness and dimensional stability of COM-PLY studs. They said that, if prices were equal, they would prefer using COM-PLY studs instead of sawn studs because there would be less waste from warping and the studs would be of uniform quality. The new studs were easily end- or toe-nailed, with less splitting than occurs with sawn studs.

Although COM-PLY studs and panels were heavier than conventional products, the builders decided that the greater weight and resistance to side-nailing would not deter them from using the new products. COM-PLY studs withstood extremes in heat and cold and in wetness and dryness with no apparent loss in strength, stiffness, or dimensional stability. Drilling holes through the cores of COM-PLY studs for plumbing and electrical wiring did not affect their strength and stiffness or the appearance of the finished walls.

Carpenters detected the superior stiffness of composite panels along the grain. Generally, they believed that the 7/16-inch-thick, composite roof sheathing was as stiff as or stiffer than 1/2-inch-thick plywood. They pointed out that the cores of composite panels were solid and free from the knot holes that sometimes occur in plywood. Furthermore, they also noted that composite roof sheathing, floor sheathing, and wall siding did not buckle even when subjected to heavy rain.

Construction of the demonstration houses proved that composite floor panels can be effectively tongued and grooved. None of the tongued and grooved edges broke, crumbled, or became distorted. Construction of the houses also showed that composite floor panels can be glued to floor joists in the same manner as plywood floor underlayment.

We recommend that the face veneers of COM-PLY studs be marked with a prohibition against cutting or notching. In addition, COM-PLY studs should be marked to indicate that their only intended use is for framing exterior walls of houses. We also recommend that composite panels be marked with a quality symbol such as the American Plywood Association's grade-trademark.

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Koehler, Gerald A., Robert H. McAlister, and Orville G. Lantz. 1957. Demonstration houses built with COM-PLY products. USDA For. Serv. Rpt. No. 177 COM-PLY Rep. 10, 27 p. Southeast. For. Exp. Sta., Asheville, N.C., and U. S. Dept. Housing and Urban Develop., Washington, D. C.

Composite studs and panels developed in the laboratory were used to build six demonstration houses in all kinds of weather. Builders found they could cut, nail, and install the composite products just like lumber studs and plywood. Composite products proved to be adaptable to various uses. Builders liked the straightness of composite studs because this quality resulted in straighter walls, tighter joints, and less waste on the job site. Carpenters generally felt composite panels were softer than the plywood they were accustomed to. The houses were built under the Experimental Housing Program of the Department of Housing and Urban Development.

KEYWORDS: Plywood, composite studs and panels, sheathing, flooring, siding, framing, experimental housing.

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The Forest Service, U. S. Department of Agriculture, is dedicated to the principle of multiple use management of the Nation's forest resources for sustained yields of wood, water, forage, wildlife, and recreation. Through forestry research, cooperation with the States and private forest owners, and management of the National Forests and National Grasslands, it strives—as directed by Congress—to provide increasingly greater service to a growing Nation.

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COM-PLY 11

REPORT

COMPARATIVE RACKING STRENGTH OF WALLS FRAMED WITH COM-PLY AND SAWN TIMBER STUDS

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COOPERATIVE RESEARCH

March 1978

Southeastern Forest Experiment Station
Asheville, North Carolina

COMPARATIVE RACKING STRENGTH OF WALLS FRAMED WITH COM-PLY AND SAWN TIMBER STUDS

by

Dick C. Wittenberg, Associate Architectural Engineer

Forestry Sciences Laboratory

Athens, Georgia

Cooperative Research by

U.S. Department of Agriculture, Forest Service

Southeastern Forest Experiment Station

and

U.S. Department of Housing and Urban Development

Division of Energy,

Building Technology and Standards

PREFACE

This report is one of a series on the possibilities of producing house framing and structural panels with particleboard cores and veneer facings. These COM-PLY or composite materials were designed to be used interchangeably with conventional lumber and plywood in homes. Research on structural framing is presently limited to COM-PLY studs but will be extended to include larger members such as floor joists.

In 1973, the home-building industry faced a shortage of lumber and plywood and consequent rising prices. Both industry and government recognized that this situation was not a temporary problem, and that long-range plans for better using the Nation's available forest resources would be necessary.

The USDA Forest Service and the U.S. Department of Housing and Urban Development accelerated cooperative research on ways to utilize the whole tree. They concentrated on composite wood products made with particleboard and veneer as a way of using not only more of the tree stem, but also using less desirable trees and a greater variety of tree species than would conventional wood products. The particleboard which comprises a large portion of the COM-PLY stud is made from ground-up wood that comes from forest residues, mill residues, or low-quality timber. Thus, such composites could greatly increase the amount of lumber and plywood available for residential construction, our major use of wood, without eroding the Nation's timber supply.

Research on composite wall framing was performed by the Wood Products Research Unit, Southeastern Forest Experiment Station, Athens, Georgia. The American Plywood Association cooperated in these studies by designing and testing composite panel products that are interchangeable with plywood. Both types of products have been incorporated in demonstration houses.

Included in this series will be reports on structural properties, durability, dimensional stability, strength, and stiffness of composite studs. Other reports will describe the overall project, compare the strength of composite and solid wood studs, suggest performance standards for composite studs, and provide construction details on houses incorporating such studs. Still others will explore the economic feasibility of manufacturing composite studs and panels and estimate the amount and quality of veneer available from southern pines. These reports, called the COM-PLY series, will be available from the Southeastern Forest Experiment Station and the U.S. Department of Housing and Urban Development.

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National Particleboard Association

COMPARATIVE RACKING STRENGTH OF WALLS FRAMED WITH COM-PLY AND SAWN TIMBER STUDS

Abstract.--Test panels framed with COM-PLY studs had greater racking strength and less deformation than those framed with spruce studs. An 8- by 8-foot frame made of COM-PLY studs and 1/2-inch-thick, CD-grade, exterior plywood sheathing met the requirements for racking strength as set forth by the Federal Housing Administration. Racking strength of panels made with the same type of plywood and framed with spruce studs did not meet the FHA requirements.

KEYWORDS: Exterior wall panels, strength of houses, wall frames, wind loads, wind resistance, rigidity of walls, wall sheathing.

Cooperative research by the U.S. Department of Housing and Urban Development and the USDA Forest Service has developed a new composite lumber product. This new structural product, called COM-PLY, will result in more efficient use of the Nation's forest resources and increase the supply of structural lumber for building homes. With the COM-PLY concept, a given amount of lumber can be produced from fewer trees than if traditional sawing methods are used. COM-PLY products are structural sandwiches with particleboard cores placed between layers of solid wood veneer (fig. 1).

Figure 1.--Configuration of a COM-PLY stud.

In this report, COM-PLY lumber is limited to 2 x 4 studs typically used to frame the exterior walls of houses. Such studs are about 20 percent veneer and 80 percent particleboard. The particleboard core can be made from forest residues, mill residues, or low-quality timber. Composite lumber utilizes almost all of the tree that comes from the forest. Even some wastes generated by sawing lumber and plywood are used in composites. COM-PLY studs are to be used as direct substitutes for conventionally sawn lumber studs and at the same spacings (fig. 2).

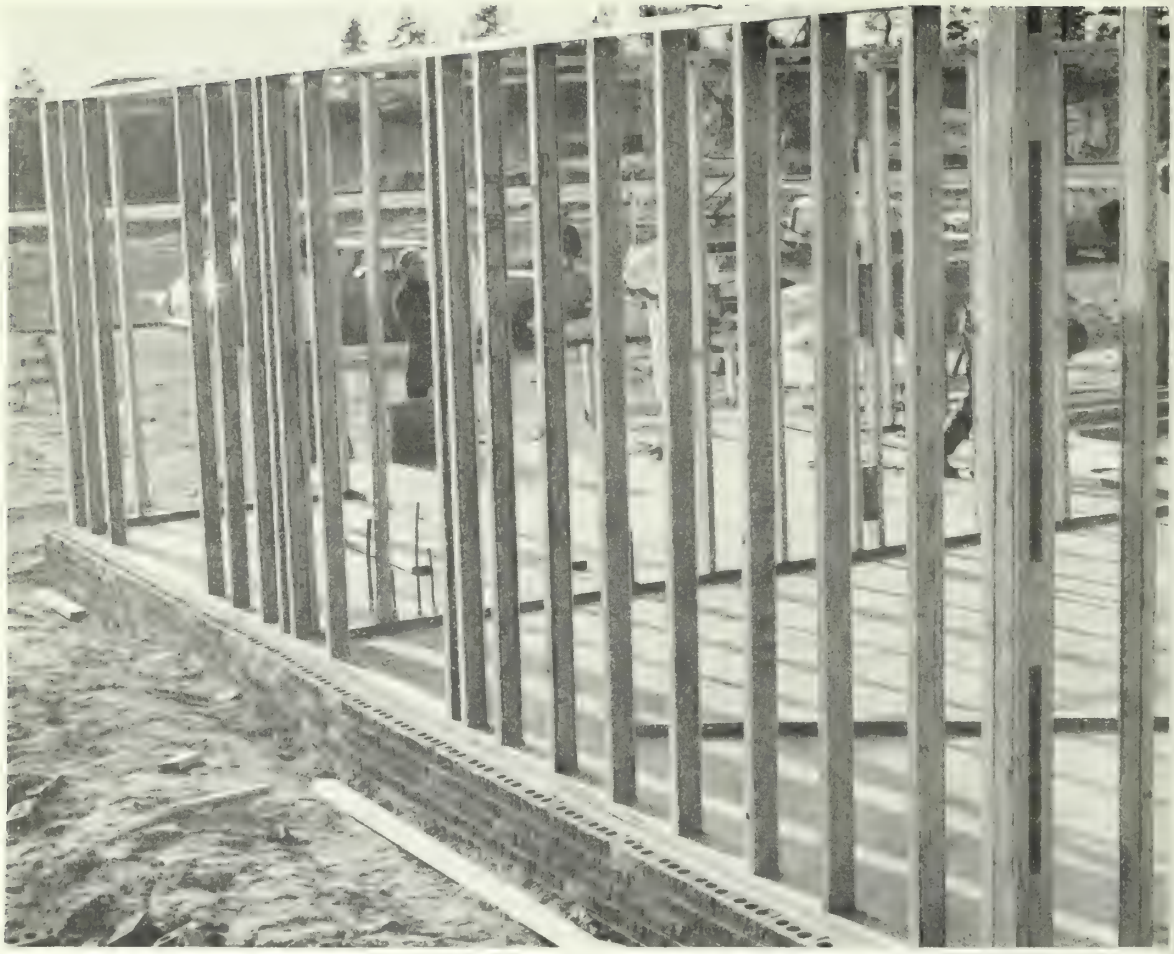


Figure 2.--COM-PLY studs installed in a house under construction.

Potential manufacturers, building code officials, and builders need to know if walls framed with COM-PLY studs will provide enough racking strength (shear strength in the plane of the panel) to resist design wind loads. This paper compares the racking strengths of plywood wall sheathing framed with COM-PLY and sawn studs in light of criteria for such strength and wall deformation as set forth by the Federal Housing Administration.

MATERIALS

Of the six panels tested, three were framed with COM-PLY studs randomly selected from 3,200 such studs made at the U.S. Plywood plant in South Boston, Va. The other three panels were framed with randomly selected, stud-grade spruce studs purchased from a local lumber dealer.

The COM-PLY studs had a core of 1-1/2-inch-thick, phenolic-bonded particleboard made by a commercial manufacturer. This three-layered board was formed by the air suspension method from wood particles processed from planer shavings, slabs, edgings, and other mill residues from southern pine. This particleboard had an average density of 40 lb/ft^3, an internal bond of 75 lb/in^2, a modulus of elasticity (in plane of panel) of 300,000 lb/in^2, a modulus of rupture (in plane of panel) of 3,400 lb/in^2, and incorporated 8 percent resin binder throughout the three layers.

Rotary-cut sheets of southern pine veneer, 4 by 8 feet and 1/6 inch thick, ere parallel-laminated with standard phenolic glue in hot presses by a plywood anufacturer. These two-ply sheets were later cut into 1-1/2-inch-wide, 8 foot- ong, 1/3-inch-thick strips at South Boston, Va., before being laminated to the -1/2-inch edges of the particleboard cores with phenol-resorcinol resin.

The panels for the racking test were the standard ones used in the ASTM E-72-74 acking test (ASTM 1974) except that the studs were spaced 24 inches instead of 16 nches on center (fig. 3). Both the panels with COM-PLY studs and those with spruce tuds were made with 1/2-inch-thick, three-ply, CD-grade southern pine sheathing onded with an exterior glue. We nailed the plywood sheathing to both groups of anels with 6d common nails spaced 6 inches on center along the panel edges and 2 inches on center along intermediate studs (fig. 4). These are the maximum stud

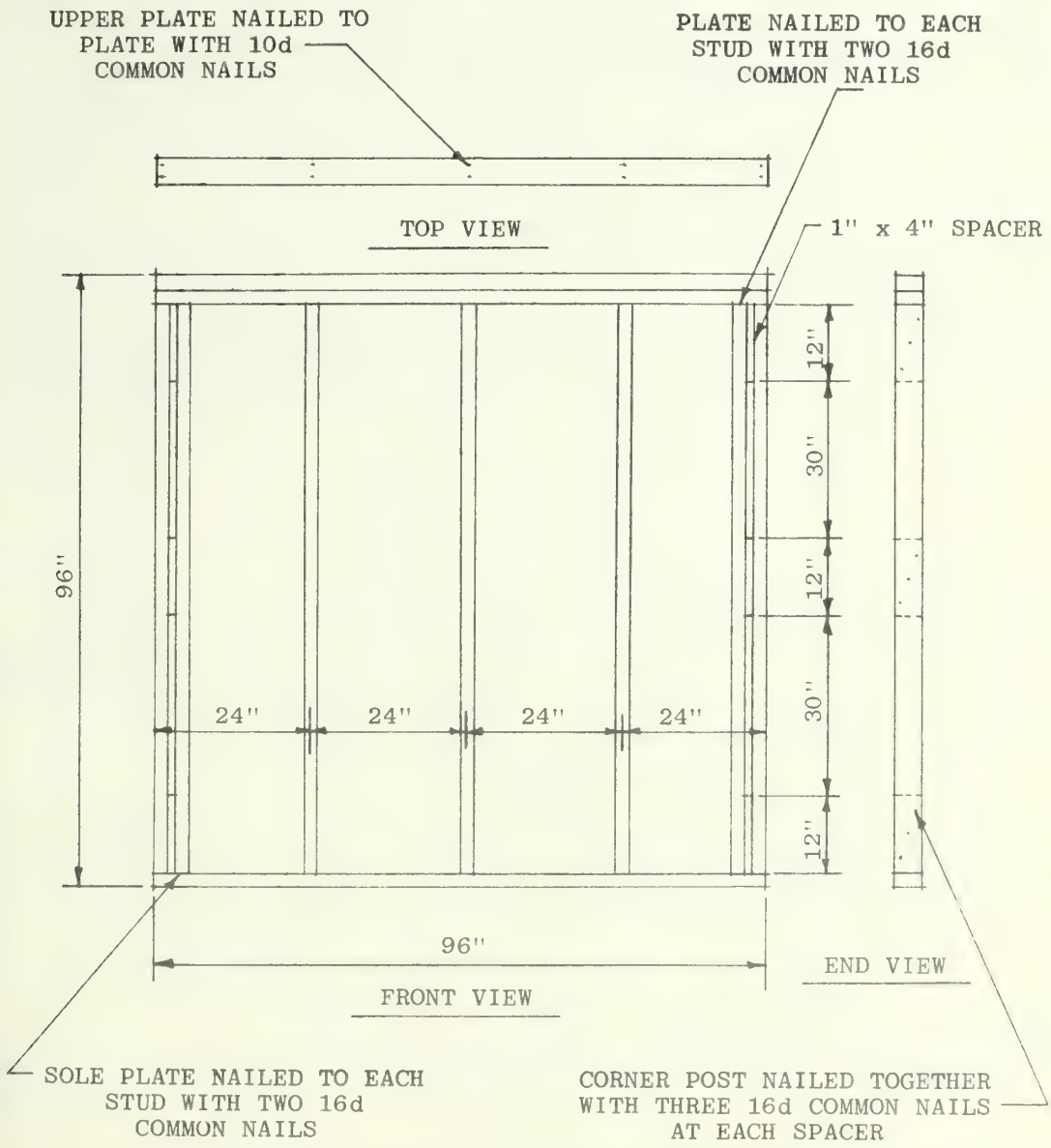


Figure 3.--General framing details for the racking test panels.

spacings and minimum nailing spacings building codes usually permit for exterior walls. Thus, Forest Service and FHA engineers wanted to investigate racking strength of the most critical construction where COM-PLY studs might commonly be used.

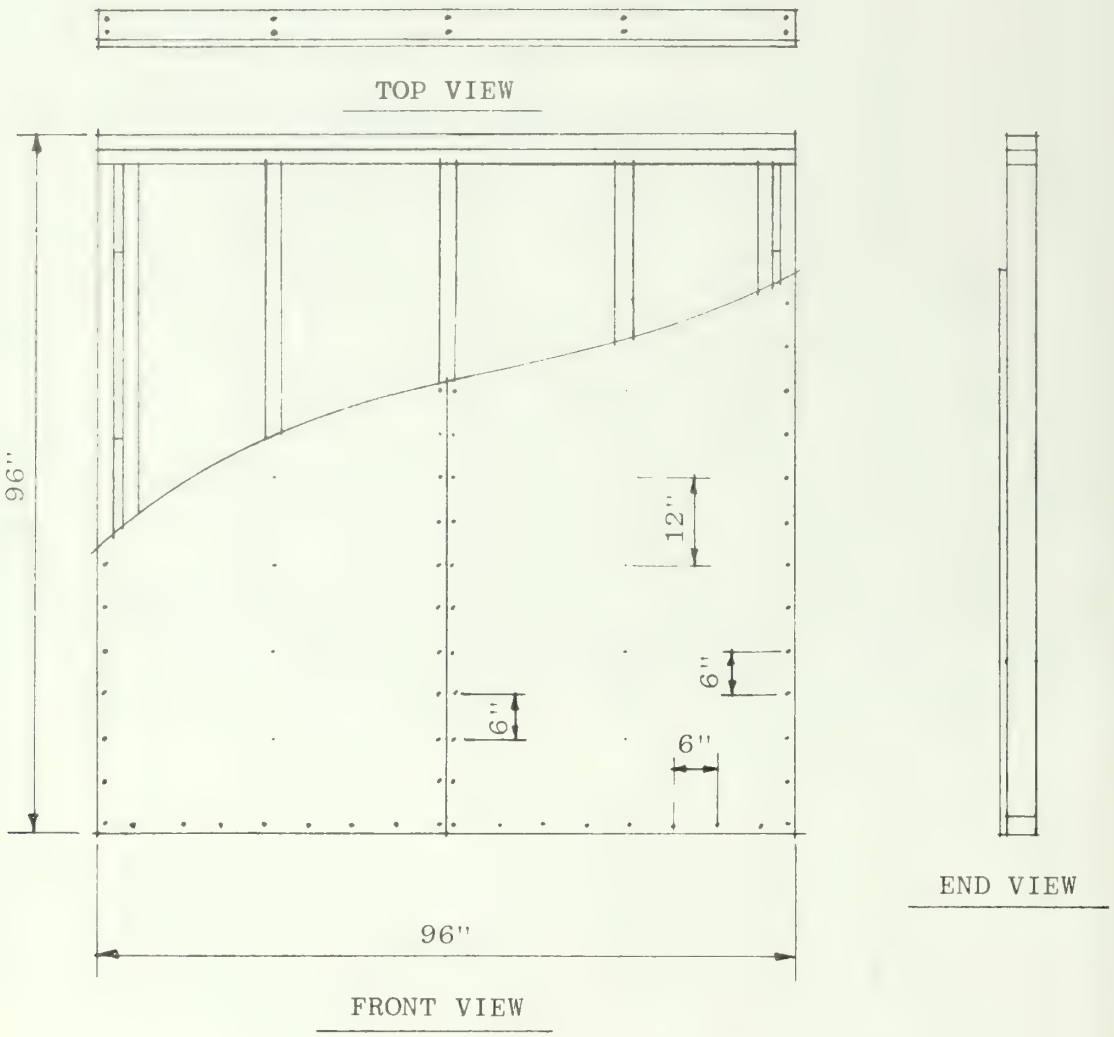


Figure 4.--Nailing details for the racking test panels.

METHODS AND PROCEDURES

TEST METHOD

The test apparatus was similar to that described in ASTM E-72-74 (ASTM 1974) except that the specimen was held horizontally instead of vertically (fig. 5).

Racking loads were applied with a hydraulic cyclinder which had been previously calibrated in a universal testing machine. Loads were applied in 400-pound increments until the panels failed, and the corresponding gage pressures were recorded.

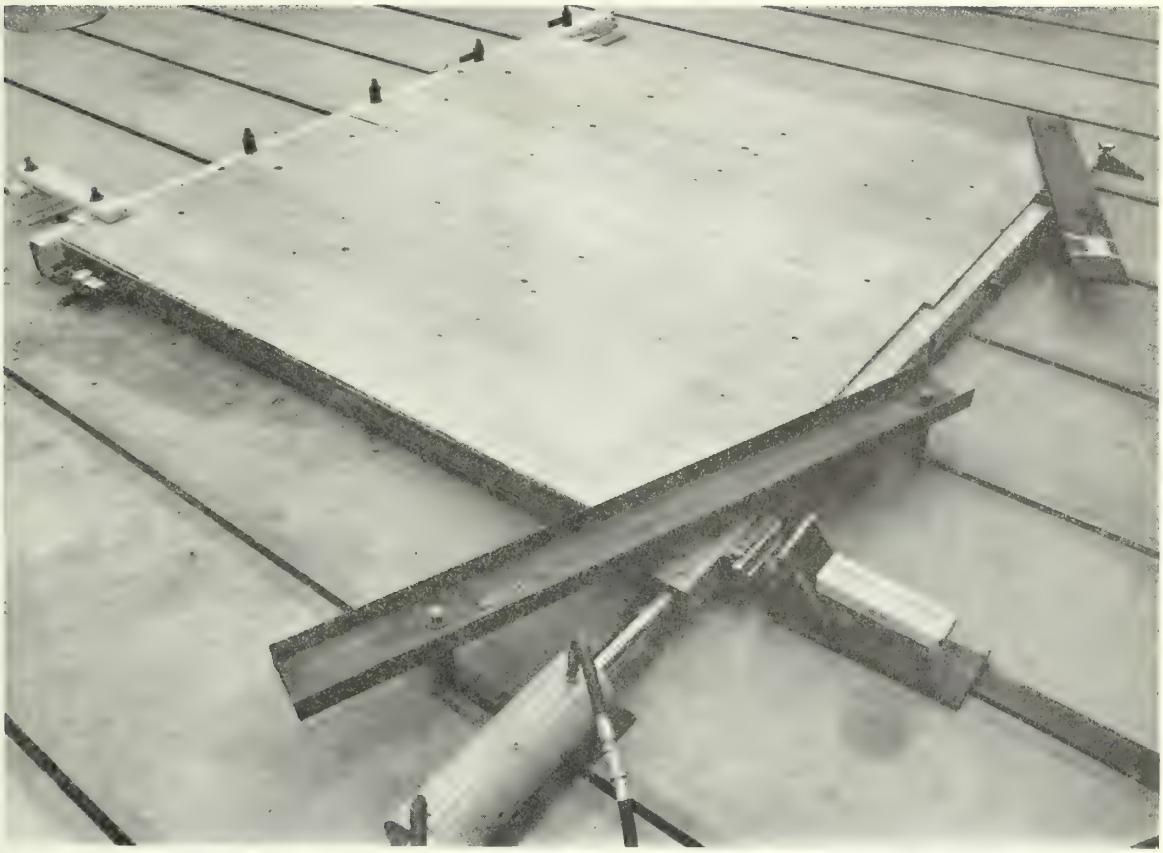


Figure 5.--Testing a panel made with composite studs for racking strength.

The double top plate of each panel was bolted to a nominal 4- x 4-inch timber. his timber rested on two roller-bearing supports, one near each end. Three hold- own devices, two with roller bearings placed along the top and one placed along he bottom plates but without roller bearings (fig. 6), prevented uplift or buckling uring the test. The roller-bearing hold-downs and the roller-bearing supports al- owed free movement in the plane of the panel without restraining racking movement.

A reaction roller bearing placed above the top plate at point A (fig. 6) pro- ided the necessary reaction. A counter reaction was provided at the diagonally pposite corner, points B and C (fig. 6), by two bearing plates, a 4- x 4-inch eam bolted to the test floor and an end-bearing block fastened to the beam. Loads ere applied to the panel through a load shoe that pressed against the 4- x 4-inch imber bolted to the top plate.

EASURING EQUIPMENT

Three dial gages, each incremented to 0.001 inch, were mounted on tripods nd used to measure the displacement of the different parts of the panel. These ial gages were located about 4 inches from the corners of the panel (fig. 6).

Gage No. 3 measured panel rotation, gage No. 2 measured any panel translation, nd gage No. 1 measured deformation of the other two gages and racking deformation f the panel. We had to extrapolate each gage reading to determine what reading ould have occurred if gages had been located at the panel corners.

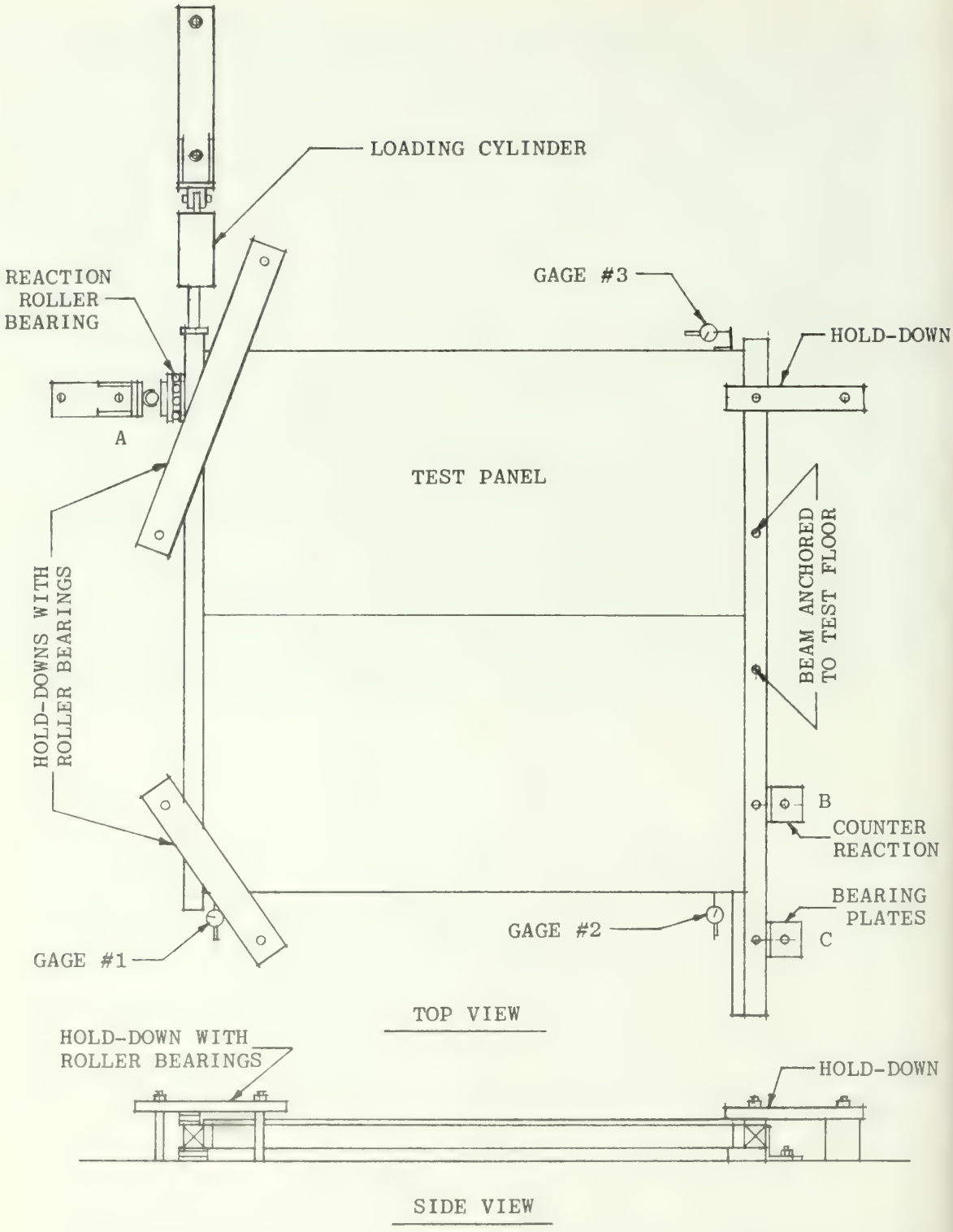
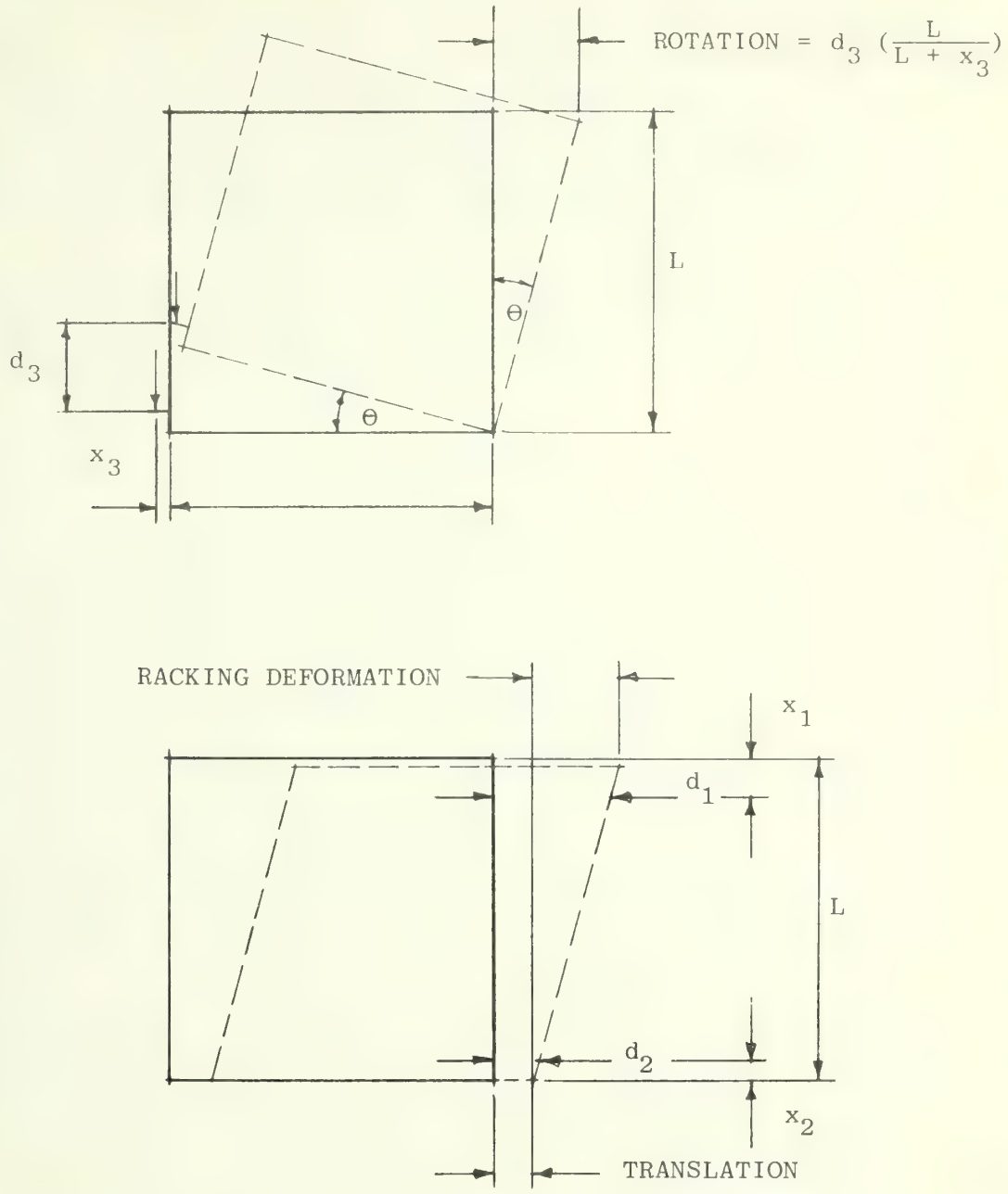


Figure 6.--Details of racking test apparatus.

Figure 7 gives the formulas for calculating racking deformation from the three gage readings.



d_1, d_2, AND d_3 = MEASURED VALUES

x_1, x_2, AND x_3 INDICATE THE DISTANCE BETWEEN DIAL GAGES AND THE ADJACENT CORNERS OF THE PANEL

$$\text{RACKING DEFORMATION} = \frac{L}{L - x_1 - x_2} (d_1 - d_2) - d_3 \left(\frac{L}{L + x_3}\right)$$

Figure 7.--Formulas for calculating racking deformation.

TEST PROCEDURES

The 4- x 4-inch timber was bolted to the top plate of the test specimen. Then the test panel and timber were placed on top of the roller-support bearings, and the beam was bolted in place on the floor. Next, the hold-downs and reaction roller bearings were placed over the corners of the test specimen, as shown in figure 6.

To apply the test loads uniformly at a constant rate of 400 pounds per minute, we used a stopwatch and constantly adjusted the rate of increase in hydraulic gage pressure. We read the dial gages at each 400-pound load increment. In accordance with the ASTM E-72-74 racking test (ASTM 1974), the specimens were loaded to 800 pounds, then unloaded, loaded to 1,600 pounds, then unloaded, and finally loaded to 2,400 pounds and again unloaded.

To measure set or inelastic racking deformation, we read the gages when 800, 1,600 and 2,400 pounds were applied and after the load was removed. Finally, load was again applied until the specimen failed. Ultimate load was reached when the specimen failed or when total deformation reached 4 inches.

RESULTS

In general, wall panels made with COM-PLY studs were slightly stronger and had less deformation when loaded than wall panels made with spruce studs. These racking tests showed that an 8- by 8-foot frame made of COM-PLY studs spaced 24 inches on center and 1/2-inch-thick, CD-grade, exterior plywood sheathing fastened to the frame with 6d common nails met the requirements for dry testing as set forth in FHA Technical Circular 12 (FHA 1949). Racking strength of panels with spruce studs spaced 24 inches on center and with identical plywood sheathing and nails did not meet these FHA requirements.

We did not perform wet racking tests because such tests are used primarily to evaluate the effect of wetting on the racking strength of panel sheathing rather than panel framing.

The average ultimate racking load was 5,250 pounds for panels with COM-PLY studs and 4,883 pounds for panels with spruce studs. FHA Circular 12 (FHA 1949) requires that a racking test panel have an average ultimate test load of 5,200 pounds. When the specimens reached ultimate load, the nailed joints fastening the plywood to the studs caused failure in both types of panels.

Table 1 shows average racking and residual deformations for test panels framed with COM-PLY and spruce studs. Because the residual deformations were recorded only after 800, 1,600 and 2,400 pounds, it was necessary to estimate the residual deformations for a 1,200-pound load from graphs of the test results (figs. 8 and 9). Both the panels with COM-PLY studs and those with spruce studs had less than the maximum racking and residual deformation allowed by FHA Circular 12 (FHA 1949). This standard requires that at a load of 1,200 pounds the average deformation must not exceed 0.2 inch and the average residual deformation must not exceed 0.1 inch; at a load of 2,400 pounds, the average deformation must not exceed 0.6 inch and the average residual deformation must not exceed 0.3 inch.

When load was applied to some of the panels, there was an initial inelastic deformation until sufficient load was applied to set the test specimen firmly against the reactor blocks. This initial inelastic deformation was substracted from the racking test data (figs. 8 and 9). The graphs show that there is very little difference in the load deformations of panels framed with the two types of studs.

Table 1.--Average racking and residual deformations for test panels framed with COM-PLY and spruce studs

Framing type	Load	Average deformation	Average residual deformation
	Pounds	----------Inch----------	
COM-PLY	1,200	0.08	0.03
	2,400	.20	.07
Spruce	1,200	.09	.03
	2,400	.24	.08

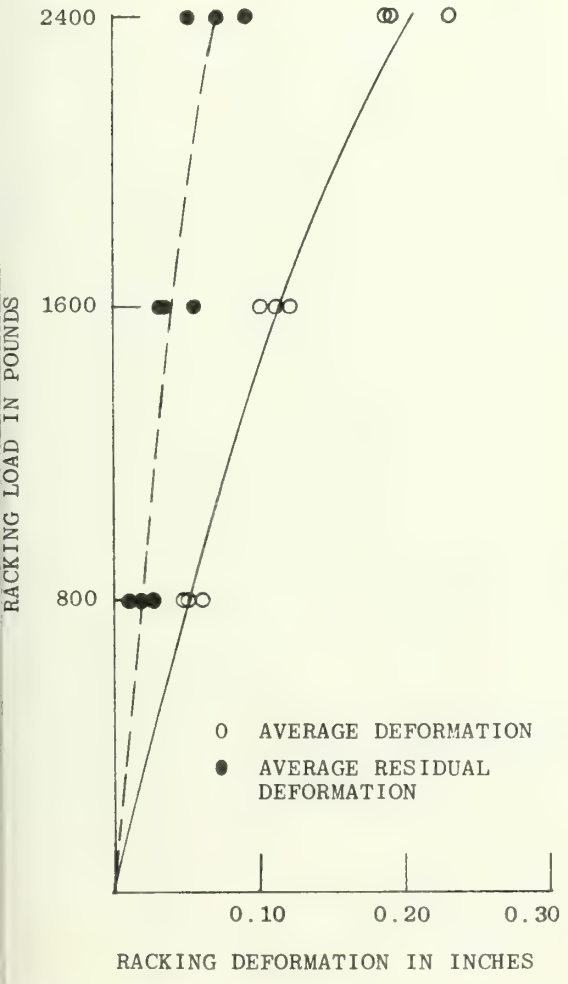


Figure 8.--Racking deformation of panels framed with COM-PLY studs.

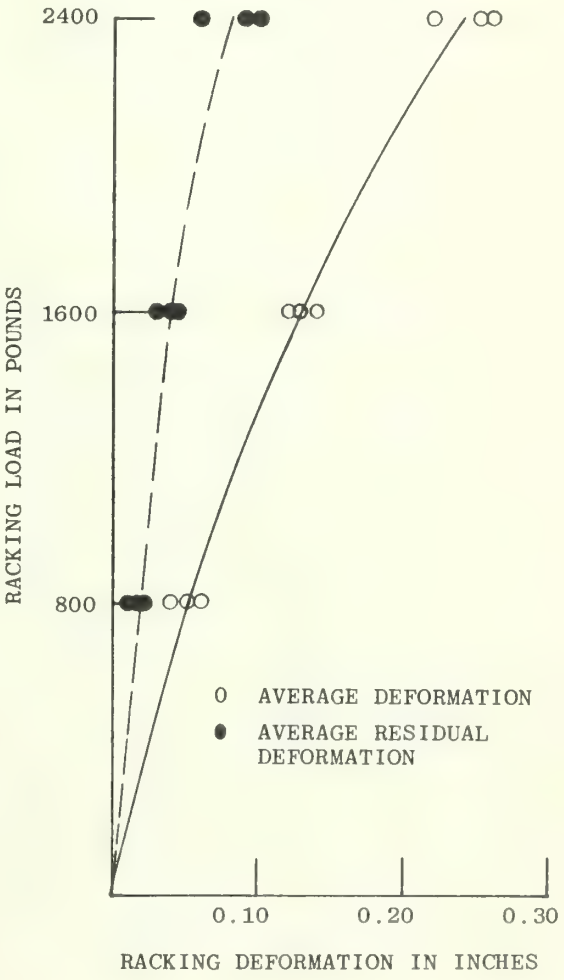


Figure 9.--Racking deformation of panels framed with spruce studs.

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KEYWORDS: Exterior wall panels, strength of houses, wall frames, wind loads, wind resistance, rigidity of walls, wall sheathing.

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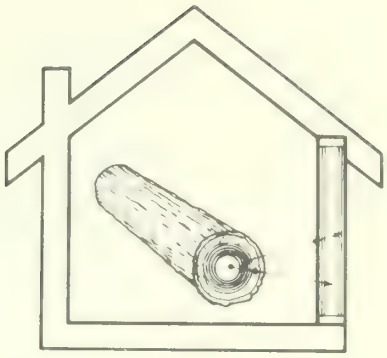

COM-PLY 9
REPORT

YIELD OF SOUTHERN PINE VENEER SUITABLE FOR COMPOSITE LUMBER AND PANELS

APR 4 1972

COOPERATIVE RESEARCH

January 1978

Southeastern Forest Experiment Station
Asheville, North Carolina

YIELD OF SOUTHERN PINE VENEER SUITABLE FOR COMPOSITE LUMBER AND PANELS

by

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Forestry Sciences Laboratory

Athens, Georgia

Cooperative Research by

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PREFACE

This report is one of a series on the possibilities of producing house framing and structural panels with particleboard cores and veneer facings. These COM-PLY or composite materials were designed to be used interchangeably with conventional lumber and plywood in homes. Research on structural framing is presently limited to COM-PLY studs but will be extended to include larger members such as floor joists.

In 1973, the home-building industry faced a shortage of lumber and plywood and consequent rising prices. Both industry and government recognized that this situation was not a temporary problem, and that long-range plans for better using the Nation's available forest resources would be necessary.

The USDA Forest Service and the U.S. Department of Housing and Urban Development accelerated cooperative research on ways to utilize the whole tree. They concentrated on composite wood products made with particleboard and veneer as a way of using not only more of the tree stem, but also using less desirable trees and a greater variety of tree species than would conventional wood products. The particleboard which comprises a large portion of the COM-PLY stud is made from chipped-up wood that comes from forest residues, mill residues, or low-quality timber. Thus, such composites could greatly increase the amount of lumber and plywood available for residential construction, our major use of wood, without eroding the Nation's timber supply.

Research on composite wall framing was performed by the Wood Products Research Unit, Southeastern Forest Experiment Station, Athens, Georgia. The American Plywood Association cooperated in these studies by designing and testing composite panel products that are interchangeable with plywood. Both types of products have been incorporated in demonstration houses.

Included in this series will be reports on structural properties, durability, dimensional stability, strength, and stiffness of composite studs. Other reports will compare the strength of composite and solid wood studs, suggest performance standards for composite studs, and provide construction details on houses incorporating such studs. Still others will explore the economic feasibility of manufacturing composite studs and panels and estimate the amount and quality of veneer available from southern pines. These reports, called the COM-PLY series, will be available from the Southeastern Forest Experiment Station and the U.S. Department of Housing and Urban Development.

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YIELD OF SOUTHERN PINE VENEER SUITABLE FOR COMPOSITE LUMBER AND PANELS

Abstract.--The dry volume and standard grades of veneer available from loblolly and slash pines are presented according to tree diameter and location within the stem. Trees 16 inches d.b.h. and smaller yield a high proportion of the grade C and better veneer required for COM-PLY products. Over 90 percent of such veneer is cut from the lower 26 feet of the stem. COM-PLY products consist of veneer faces and particleboard cores, which can be made from forest and mill residues. A typical stand of southern pine will yield more than enough suitable veneer so that over 90 percent of the total stand volume can be used in making composite products.

KEYWORDS: COM-PLY studs, COM-PLY panels, veneer grade, veneer blocks, veneer yield.

Through cooperative research, the USDA Forest Service, the Department of Housing and Urban Development, and several manufacturers of forest products have developed composite studs and panels. These new structural products, called COM-PLY, are designed for more efficient use of our forest resources.

COM-PLY products are structural sandwiches with a particleboard core placed between layers of solid wood veneer (fig. 1). The particleboard in composite studs and panels can be made from low-quality timber and material not suitable for veneer. The major advantage of composite products is that all of the harvested tree can be used in their manufacture. Furthermore, production of COM-PLY products generates essentially no residue except bark.

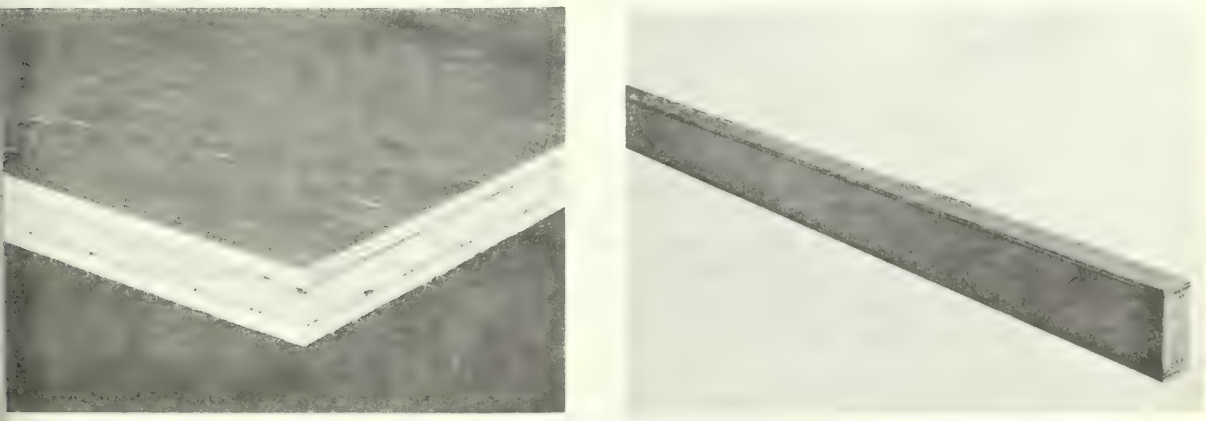

Figure 1.--Construction of a COM-PLY panel (left) and a COM-PLY stud (right).

This report, directed to potential manufacturers of composite lumber and panels, describes the dry cubic footage and grades of veneer available from loblolly (*Pinus taeda* L.) and slash (*P. elliottii* Engelm.) pines according to diameter and location within the stem. These two species are considered to be representative of southern pines in general. Wittenberg (1977) has shown that standard[1/]

[1/] In this report, standard refers to veneer grades as defined by the American Plywood Association (1974).

veneer, grade C and better, has sufficient strength and stiffness to be used in composite 2 x 4 studs. Composite panels would be made from various grades of veneer, depending on intended use.

PROCEDURES

A research program on timber quality now underway at the Forestry Sciences Laboratory in Athens, Georgia, has developed a system for predicting veneer yields by grades from southern pines. The present report combines data on grade yield from four studies conducted under that program.

Although the methods of selecting study trees and grading veneer are described in detail by Schroeder and Clark (1970), they may be summarized as follows: The researchers selected slash pines ranging from 10 to 22 inches d.b.h. from two locations near Waycross, Georgia. Loblolly pines ranging from 10 to 22 inches d.b.h. came from natural forest stands in southeastern Louisiana and Washington County, North Carolina.

Before being sent to one of four plywood mills, each log was diagramed as to number and position of veneer blocks (fig. 2). The trees were then debarked, bucked, tagged, and steamed before being peeled. A grader from the American Plywood Association supervised the veneer grading.

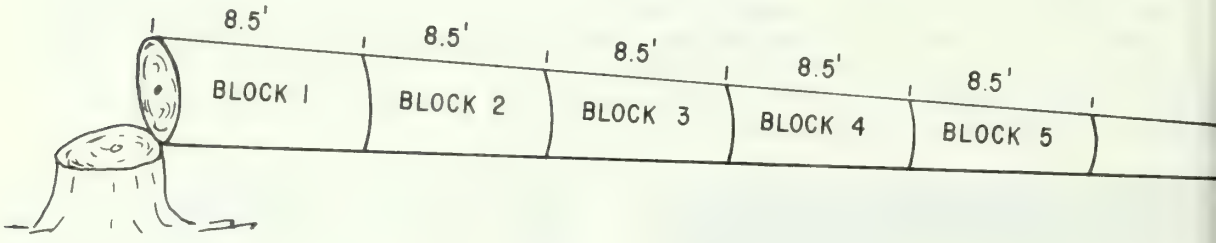

Figure 2.--Diagram of veneer blocks measured on stem.

Data from 151 loblolly and slash pines were used in the present report. From these data, summaries were developed on veneer yields by grade, block number, block diameter, and tree d.b.h. These summaries and the conclusions drawn from them form the basis of the present report.

RESULTS AND DISCUSSION

The results of this study represent a wide range of tree diameters, site classes, and geographic locations. The yields, grades, and volumes in table 1 show what can probably be expected on an industry-wide basis. Note that the trees with smaller diameters (16 inches d.b.h. and less) yield a high proportion of grade C and better veneer. This is the quality of veneer required for producing composite lumber.

Potential manufacturers of composite products can use the information presented in table 1 to determine the quantity of veneer that can be produced from any natural stand of southern pine for which the diameter distribution is known. Table 2 shows the average yield of grade C and better veneer from a typical stand

f southern pine. The regression equation shown in table 2 can be used to calculate he green volume of southern pine to a 4-inch d.i.b. (diameter inside bark) top.

Table 1.--Average dry cubic footage of veneer by grade and tree diameter class in southern pines (loblolly and slash)

Tree diameter class (inches)	Sample trees	Veneer grade				Green volume of veneer blocks
		AB	C	D	Fishtail	
	No.	Cubic feet/tree				
10	13	0.6	1.8	0.4	0.3	9.8
12	25	1.6	4.6	1.3	.5	19.1
14	28	2.5	7.9	4.8	1.2	32.4
16	23	4.4	10.1	9.0	1.6	46.0
18	32	8.1	10.0	13.2	2.0	57.2
20	17	10.0	10.8	18.2	2.3	68.8
22	13	12.3	13.9	23.9	2.7	85.1

This typical stand of southern pine yields 412 cubic feet of dry grade C and etter veneer per acre from a total tree volume of 1,590 cubic feet. Notice that he veneer block volume per acre is about 1,350 cubic feet. Thus, logging to a -inch top (d.i.b.) would provide 240 cubic feet of green wood per acre in addition o that in the veneer blocks.

Researchers estimate that the 412 cubic feet of dry veneer per acre loses bout 10 percent in manufacturing, leaving about 370 cubic feet of veneer. The ,590 cubic feet of green volume per acre shrink to about 1,350 cubic feet after rying.

A COM-PLY stud is composed of about 20 percent veneer and 80 percent particle- oard. The 1,350 cubic feet of dry volume per acre from a typical stand would yield bout 270 cubic feet of grade C and better veneer if whole tree stems were used for OM-PLY studs. Even after allowing for a 10 percent reduction in veneer volume from anufacturing losses, there is an excess of about 100 cubic feet of veneer per acre. hus, an additional volume of material suitable for particleboard, roughly 500 cubic eet per acre, would be needed to use up all of the veneer in making COM-PLY studs.

This material could come from sound wood in crooked and rough trees that are sometimes left in the woods or from milling residues in other operations.

Table 2.--Average yield of grade C and better veneer per acre, by tree diameter class, from a typical natural stand of southern pine

Tree diameter class (inches)	Stems per acre[1/]	Dry volume C & better veneer per tree	Dry volume C & better veneer per acre	Green volume of veneer blocks per tree	Green volume of veneer blocks per acre	Green volume of individual trees to 4-inch d.i.b.[2/]	Green volume of trees per acre
	No.	Cubic feet					
10	23.7	2.4	56.9	9.8	232.2	15.1	357.9
12	17.2	6.2	106.2	19.1	328.5	21.8	375.0
14	10.6	10.4	110.2	32.4	343.4	34.6	366.8
16	4.7	14.5	68.1	46.0	216.2	48.1	226.1
18	2.0	18.1	36.2	57.2	114.4	63.4	126.8
20	.9	20.8	18.7	68.8	61.9	84.3	75.9
22	.6	26.2	15.7	85.1	51.1	102.9	61.7
Total	--	--	412.0	--	1,347.7	--	1,590.2

[1/] Unpublished Forest Survey data on file, Forest Service, USDA, Washington, D.C.

[2/] $LOG_{10} V = - 2.28937 + 0.92775 LOG_{10} [D^2 H]$, where V = green volume of individual trees to a 4-inch d.i.b. top, D = diameter at breast height, and H = height to 4-inch d.i.b.

A 1/2-inch-thick composite panel with 0.1-inch-thick veneer faces requires about 40 percent veneer and 60 percent particleboard. As previously noted, producers of COM-PLY panels would use veneer of all grades, depending on intended use. The volume of full-length veneer of all grades from a typical, natural stand of southern pine would amount to 595 cubic feet per acre (table 3). Manufacturing losses in a panel operation would average about 16 percent (Woodfin 1973); therefore, the net volume of veneer would be about 500 cubic feet per acre or 37 percent of the total dry volume of the stand. Consequently, a producer of composite panels could use about 92 percent of the total stand volume and 100 percent of the veneer block volume.

Data on the dry cubic footage of veneer blocks, peeling residue, blocks too small to peel, and veneer from a typical stand of southern pine indicate that the typical stand of such trees yields less than 50 percent veneer (table 3). Over half of the total wood volume is peeling residues and small logs from tops.

The plywood industry's major problems of low yields and large quantities of residues are illustrated in figure 3. The same data illustrate the advantages of composite products: Because the solid veneer in such products amounts to only 40 percent or less, manufacturers can utilize the whole tree for the first time. The information provided in table 3 can be used in analyzing the economic feasibility of manufacturing composite products.

Yield of the various grades of veneer can also be predicted according to location within the tree stem. The highest grade of veneer will be cut from the blocks with the fewest defects. Generally, veneer blocks of the best quality come from the lower part of the stem. However, grade yield can also be affected by taper, persistent limbs, fire scars, decay patterns, and logging damage.

Table 3.--Average dry volume of veneer and residues from a typical, natural stand of southern pine[1/]

Item	Yield per acre	Proportion of total stand volume
	Cubic feet	Percent
A & B veneer	121.5	9.0
C veneer	291.1	21.5
D veneer	182.1	13.5
Total full-length veneer	594.7	44.0
Fishtail	43.6	3.2
Total veneer	638.3	47.2
Peeling residue	507.5	37.6
Total block volume	1145.8	84.8
Top log residue	205.8	15.2
Total tree volume	1351.6	100.0

[1/]Based on per-acre values for number of trees, block volume, and tree volume in a typical, natural stand of southern pine.

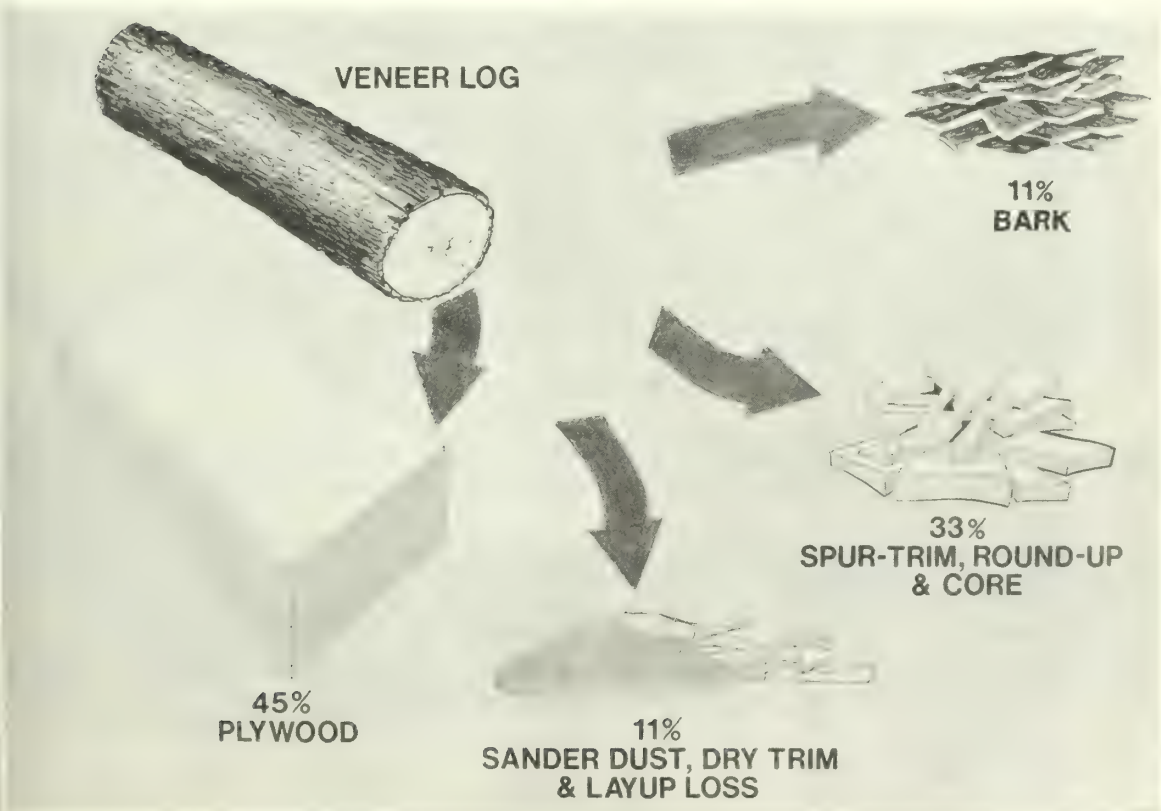

Figure 3.--Amount of usable wood and residues from a typical log during the manufacture of plywood.

The percentage of veneer that is grade C and better drops dramatically above the third block in the stem (fig. 4). Furthermore, the average amount of grade C and better veneer contained in blocks above the first four blocks (34 feet) of merchantable stem is negligible. Average yields by grade demonstrate that the first three blocks of the stem are definitely the most important to consider in producing veneer for COM-PLY products.

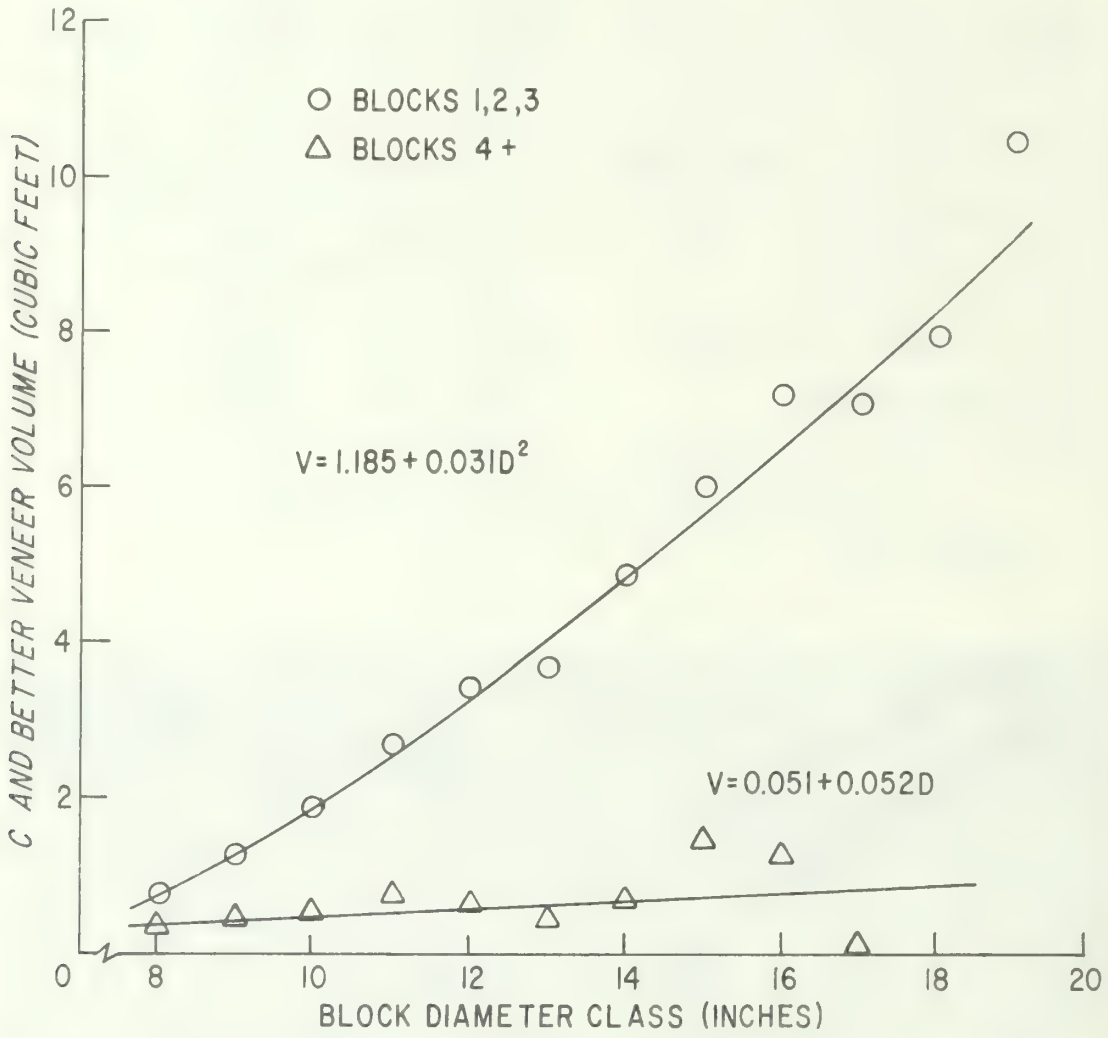

Figure 4.--Average yield of grade C and better veneer as related to block diameter and relative block position within the stem.

Researchers may be interested in grade yields for loblolly and slash pine. This information is presented in the Appendix (tables 4 through 12). These data are broken down by species, tree d.b.h. class, block diameter, and block location; they are summarized by cubic footage and percentage yields. With these data, Forest Survey[2/] information on stand characteristics by state and county can be used to estimate veneer yields by grade for specific areas.

[2/] Unpublished data on file, Forest Service, USDA, Washington, D.C.

CONCLUSIONS

The following conclusions can be drawn from the data presented:

1. A typical stand of loblolly or slash pine will have a total-tree green volume per acre of 1,590 cubic feet to a 4-inch top and will yield about 412 cubic feet per acre of dry, grade C and better veneer.

2. Composite studs are about 20 percent veneer and 80 percent particleboard. About 30 percent of the volume in a typical stand of southern pine will be grade C and better veneer. Thus, if the entire stand is used for COM-PLY studs, there will be a surplus of veneers when the veneer logs are peeled. Additional wood suitable for the particleboard core will be required if this surplus veneer is used for composite studs.

3. About 92 percent of the volume in a typical stand of southern pine can be used in the manufacture of COM-PLY panels 1/2-inch thick with 0.1-inch-thick veneers. This is over twice the volume of conventional plywood that can be produced from the same trees, a difference that should interest owners of plywood plants faced with limited timber supplies.

4. In slash and loblolly pine, over 90 percent of the grade C and better veneer is produced from the lower 26 feet of the stem, regardless of its diameter class.

5. Loblolly and slash pines in the 10- to 16-inch diameter classes yield a higher proportion of grade C and better veneer than do larger trees. Thus, wide composite lumber can be produced from the smaller trees, whereas wide sawn lumber can be produced only from large-diameter logs, which are in short supply.

6. From veneer blocks less than 10 inches in diameter, the yield of dry veneer is less than 50 percent of the green block volume.

7. Over half the volume of a typical stand of southern pine is peeling residue and top logs less than 8 inches in diameter.

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APPENDIX

The data contained in the Appendix tables are intended for researchers interested in detailed information on the veneer yields by grade for loblolly and slash pines.

Table 4.--Average dry cubic footage of veneer by grade and diameter class in loblolly pines

Tree diameter class (inches)	Sample trees	Veneer grade				Merchantable volume
		AB	C	D	Fishtail	
	No.	Cubic feet/tree				
10	8	0.6	1.8	0.2	0.3	9.3
12	12	1.5	4.6	.8	.5	19.6
14	14	2.4	8.4	4.2	1.1	33.3
16	11	4.7	10.0	8.2	1.6	47.2
18	15	7.6	9.6	13.3	1.9	55.7
20	11	9.1	9.9	15.6	2.2	64.7
22	7	11.7	13.4	19.4	2.5	80.2

Table 5.--Average dry cubic footage of veneer by grade and diameter class in slash pine

Tree diameter class (inches)	Sample trees	Veneer grade				Merchantable volume
		AB	C	D	Fishtail	
	No.	Cubic feet/tree				
10	5	0.6	1.8	0.7	0.3	10.6
12	13	1.7	4.5	1.9	.6	18.6
14	14	2.5	7.5	5.4	1.2	31.6
16	12	4.1	10.2	9.8	1.5	44.9
18	17	8.6	10.4	13.1	2.0	58.6
20	6	11.5	12.4	22.9	2.6	76.3
22	6	13.0	14.6	29.3	2.9	90.7

Table 6.--Percentage yield of southern pine veneer by grade and location of veneer block within the stem

Block (No.)	Sample blocks	Veneer grade			Total veneer	Block volume
		AB	C	D		
	No.	----------Percent of block volume----------				Cubic feet
1	151	22.9	25.3	6.6	57.8	10.80
2	151	22.4	30.7	10.7	66.2	8.22
3	143	11.3	22.9	23.3	60.4	7.78
4	136	2.2	14.4	36.2	56.2	7.13
5	124	.6	7.3	36.0	47.8	6.47
6	101	.3	3.2	34.2	42.5	5.62
7	62	.2	2.8	26.7	35.1	4.98
8	12	.0	11.4	23.1	40.9	4.28

Table 7.--Average veneer yield by grade, block diameter, and block number in loblolly and slash pines[1/]

Block diameter class (inches)	AB grade		C grade		D grade		Fishtail		Total block volume	
	Block 1, 2, or 3	Block 4 +	Block 1, 2, or 3	Block 4 +	Block 1, 2, or 3	Block 4 +	Block 1, 2, or 3	Block 4 +	Block 1, 2, or 3	Block 4 +
	Cubic feet/block									
8	0.13	0.0	0.64	0.38	0.23	0.48	0.11	0.13	3.41	3.44
9	.32	.03	.96	.41	.44	.96	.12	.20	4.26	4.23
10	.52	.0	1.43	.51	.41	1.40	.16	.27	5.14	5.13
11	.75	.08	1.95	.72	.45	1.85	.22	.26	6.37	6.16
12	1.08	.18	2.33	.43	.77	3.07	.24	.26	7.35	7.34
13	1.56	.06	2.19	.47	1.60	3.84	.26	.28	8.97	8.49
14	2.02	.10	2.87	.63	1.37	3.95	.30	.43	10.11	9.76
15	2.87	.34	3.20	1.21	1.51	4.88	.33	.40	12.09	11.11
16	3.90	.11	3.33	1.17	1.31	5.24	.36	.46	13.54	12.83
17	3.77	.0	3.38	.13	2.41	8.82	.38	.26	15.09	13.46
18	4.26	--	4.15	--	2.95	--	.35	--	16.75	--
19	4.99	--	5.55	--	1.94	--	.54	--	20.40	--

[1/] Based on data from 151 loblolly and slash pines.

Table 8.--Percentage yield of southern pine veneer from the first three blocks by block diameter and grade

Block diameter class (inches)	Sample blocks	Veneer grade			Total veneer	Green veneer block volume
		AB	C	D		
	No.	-----Percent of block volume-----				Cubic feet
8	29	3.8	18.8	6.7	32.3	3.41
9	42	7.5	22.5	10.3	43.2	4.26
10	50	10.1	27.8	8.0	49.0	5.14
11	46	11.8	30.6	7.1	52.9	6.37
12	47	14.8	31.7	10.5	60.1	7.35
13	49	17.4	24.4	17.8	62.5	8.97
14	54	20.0	28.4	13.6	64.9	10.11
15	46	23.7	26.5	12.5	65.4	12.09
16	27	28.8	24.6	9.7	65.7	13.54
17	28	25.0	22.4	16.0	65.8	15.09
18	19	25.4	24.8	17.6	69.9	16.75
19	8	24.5	27.2	9.5	63.9	20.40

Table 9.--Average veneer yields in loblolly pine by grade and block diameter when all blocks are considered

Block diameter class (inches)	Sample blocks	Veneer grade				Total veneer	Block volume
		AB	C	D	Fishtail		
	No.	----------Cubic feet/block----------					
8	48	0.07	0.56	0.26	0.12	1.01	3.42
9	60	.12	.61	.65	.13	1.51	4.12
10	67	.15	.87	1.03	.22	2.28	5.12
11	54	.30	1.44	1.03	.25	3.02	6.19
12	46	.68	1.43	1.88	.23	4.22	7.29
13	48	.80	1.42	2.61	.22	5.04	8.61
14	41	1.56	1.81	1.90	.33	5.59	9.97
15	34	2.01	2.42	2.25	.39	7.06	11.65
16	16	2.21	2.42	2.40	.39	7.42	12.97
17	18	3.14	2.56	3.10	.40	9.20	14.71
18	12	4.76	3.57	2.47	.40	11.20	16.80
19	4	4.19	6.90	.68	.59	12.36	19.62

Table 10.--Average veneer yields in loblolly pine by grade and block diameter when only the first three blocks are considered

Block diameter class (inches)	Sample blocks	Veneer grade				Total veneer	Block volume
		AB	C	D	Fishtail		
	No.	Cubic feet/block					
8	19	0.18	0.67	0.09	0.11	1.06	3.41
9	20	.32	.90	.31	.11	1.64	4.16
10	24	.43	1.45	.23	.16	2.27	5.15
11	25	.58	2.02	.36	.22	3.19	6.26
12	24	1.22	2.26	.70	.19	4.38	7.36
13	24	1.49	2.23	1.56	.19	5.47	8.72
14	29	2.14	2.27	1.25	.36	6.02	10.08
15	23	2.88	3.20	1.14	.37	7.59	11.92
16	10	3.46	3.17	.98	.39	8.01	12.99
17	16	3.53	2.87	2.56	.40	9.37	14.83
18	12	4.76	3.57	2.47	.40	11.20	16.80
19	4	4.19	6.90	.67	.59	12.36	19.62

Table 11.--Average veneer yields in slash pine by grade and block diameter when all blocks are considered

Block diameter class (inches)	Sample blocks	Veneer grade				Total veneer	Block volume
		AB	C	D	Fishtail		
	No.	Cubic feet/block					
7	2	0.00	0.02	0.38	0.20	0.60	3.10
8	46	.01	.37	.54	.14	1.05	3.45
9	62	.14	.59	.90	.21	1.85	4.36
10	55	.28	.90	.94	.23	2.37	5.16
11	59	.40	1.02	1.51	.24	3.17	6.29
12	50	.57	1.30	2.00	.27	4.14	7.40
13	44	.93	1.36	2.69	.32	5.29	8.89
14	39	1.23	2.49	2.54	.35	6.61	10.03
15	30	2.33	2.89	2.70	.31	8.23	12.00
16	18	3.92	3.30	1.87	.37	9.47	13.76
17	16	3.06	3.08	4.03	.31	10.48	14.91
18	7	3.39	[illegible]	3.78	.28	12.59	16.68
19	4	5.79	4.20	3.20	.49	13.69	21.18

Table 12.--Average veneer yields in slash pine by grade and block diameter when only the first three blocks are considered

Block diameter class (inches)	Sample blocks	Veneer grade				Total veneer	Block volume
		AB	C	D	Fishtail		
	No.	Cubic feet/block					
8	10	0.03	0.58	0.47	0.10	1.19	3.40
9	22	.32	1.02	.56	.14	2.03	4.35
10	26	.60	1.42	.58	.16	2.76	5.14
11	21	.95	1.86	.56	.21	3.58	6.51
12	23	.94	2.40	.83	.28	4.46	7.34
13	25	1.62	2.15	1.64	.33	5.74	9.21
14	25	1.89	3.55	1.52	.23	7.19	10.15
15	23	2.85	3.20	1.88	.30	8.23	12.27
16	17	4.15	3.43	1.50	.34	9.43	13.86
17	12	4.08	4.06	2.21	.34	10.68	15.43
18	7	3.39	5.14	3.78	.28	12.59	16.68
19	4	5.79	4.20	3.20	.49	13.69	21.18

McAlister, Robert H., and Michael A. Taras
1978. Yield of southern pine veneer suitable for composite lumber and panels. U.S. Dep. Agric. For. Serv. Res. Pap. SE-179, COM-PLY Rep. 9, 15 p. Southeast. For. Exp. Stn., Asheville, N. C., and U.S. Dep. Housing and Urban Develop., Washington, D. C.

The dry volume and standard grades of veneer available from loblolly and slash pines are presented according to tree diameter and location within the stem. Trees 16 inches d.b.h. and smaller yield a high proportion of the grade C and better veneer required for COM-PLY products. Over 90 percent of such veneer is cut from the lower 26 feet of the stem. COM-PLY products consist of veneer faces and particleboard cores, which can be made from forest and mill residues. A typical stand of southern pine will yield more than enough suitable veneer so that over 90 percent of the total stand volume can be used in making composite products.

KEYWORDS: COM-PLY studs, COM-PLY panels, veneer grade, veneer blocks, veneer yield.

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REPORT

STRUCTURAL PROPERTIES
OF COMPLY STUDS

COOPERATIVE RESEARCH

May 1978

Southeastern Forest Experiment Station
Asheville, North Carolina

STRUCTURAL PROPERTIES OF COM-PLY STUDS

by

Robert H. McAlister, Principal Wood Scientist

Forestry Sciences Laboratory

Athens, Georgia

Cooperative Research by

U.S. Department of Agriculture, Forest Service

Southeastern Forest Experiment Station

and

U.S. Department of Housing and Urban Development

Division of Energy,

Building Technology and Standards

PREFACE

This report is one of a series on the possibilities of producing house framing and structural panels with particleboard cores and veneer facings. These COM-PLY or composite materials were designed to be used interchangeably with conventional lumber and plywood in homes. Research on structural framing is presentl limited to COM-PLY studs but will be extended to include larger members such as floor joists.

In 1973, the home-building industry faced a shortage of lumber and plywood and consequent rising prices. Both industry and government recognized that this situation was not a temporary problem, and that long-range plans for better using the Nation's available forest resources would be necessary.

The USDA Forest Service and the U.S. Department of Housing and Urban Development accelerated cooperative research on ways to utilize the whole tree. They concentrated on composite wood products made with particleboard and veneer as a way of using not only more of the tree stem, but also using less desirable trees and a greater variety of tree species than would conventional wood products The particleboard which comprises a large portion of the COM-PLY stud is made fro chipped-up wood that comes from forest residues, mill residues, or low-quality timber. Thus, such composites could greatly increase the amount of lumber and plywood available for residential construction, our major use of wood, without eroding the Nation's timber supply.

Research on composite wall framing was performed by the Wood Products Research Unit, Southeastern Forest Experiment Station, Athens, Georgia. The American Plywood Association cooperated in these studies by designing and testing composite panel products that are interchangeable with plywood. Both types of products have been incorporated in demonstration houses.

Included in this series will be reports on structural properties, durability, dimensional stability, strength, and stiffness of composite studs. Other reports will describe the overall project, compare the strength of composite and solid wood studs, suggest performance standards for composite studs, and provide construction details on houses incorporating such studs. Still others will explore the economic feasibility of manufacturing composite studs and panels and estimate the amount and quality of veneer available from southern pines. These reports, called the COM-PLY series, will be available from the Southeastern Forest Experiment Station and the U.S. Department of Housing and Urban Development.

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STRUCTURAL PROPERTIES OF COM-PLY STUDS

Abstract.--The major strength properties of COM-PLY studs were evaluated from the standpoint of engineering and design. The modulus of elasticity (MOE) of all component parts of 12 COM-PLY 2 x 4's was determined before fabrication. After fabrication, tests of static bending, compression parallel to grain, compression perpendicular to grain, and shear were made according to standards of the American Society for Testing and Materials. Results indicated that these strength properties of COM-PLY 2 x 4's are comparable to those of 2 x 4's of solid wood.

KEYWORDS: Modulus of elasticity, strength and stiffness, static bending, compression, shear, veneer, particleboard.

The USDA Forest Service, the Department of Housing and Urban Development, and veral manufacturers of forest products have cooperated in developing a new composite lumber product. This product, the COM-PLY stud, is a structural sandwich th a particleboard core placed between layers of solid wood veneer (fig. 1).

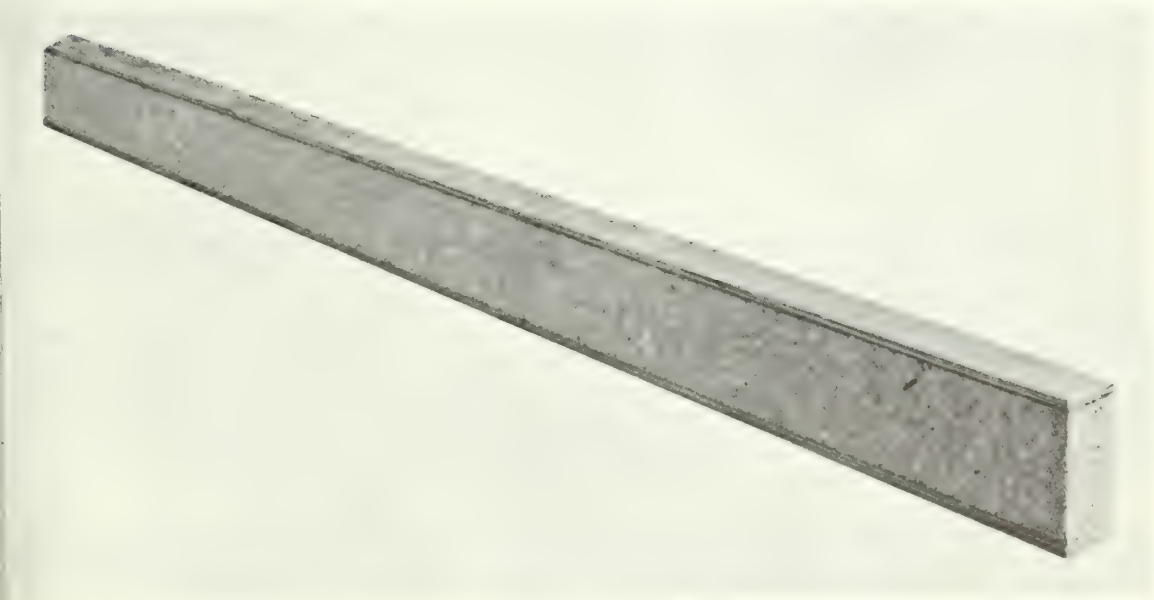


Figure 1.--A typical COM-PLY stud.

COM-PLY studs are about 20 percent veneer and 80 percent particleboard. Beuse of their composite construction, these studs could eventually lead to more ficient use of the Nation's forest resources. While the veneer facings must be ile from the strong, clear wood in the outer portions of healthy trees, the particleboard core can be made from forest and mill residues and low-quality timber.

Although major progress has recently been made in using slabs, edgings, and neer cores for paper and particleboard, unused plant residues still constitute izable potential resource. Another untapped resource is the large quantity of gging residues left in the woods because of the high costs of recovery. Other

unused resources are crooked trees and sound wood from dead and decaying trees. All of these materials can be chipped up and converted to particleboard cores for COM-PLY studs.

Initial studies of the new product were limited to COM-PLY 2 x 4 studs designed as framing for the exterior walls of houses. For such studs, Blomquist and others (1976) devised Performance Standards based on a combined axial and bending load test. This test simulates the forces that act on a stud in an exterior wall, but the data derived cannot be used directly to calculate fiber stress at the proportional limit or modulus of rupture (MOR) in bending--values that designers and engineers need if they are to compare the strength properties of composite and solid wood members.

COM-PLY studs might be used for blocking, posts, headers, or plates. Thus, building code officials and engineers need to know whether COM-PLY studs have sufficient structural strength for these uses. The strength properties of greates interest to engineers are: (1) axial load-bearing capacity, or strength in compression parallel to the grain of the face plies; (2) bearing, or strength in compression perpendicular to the grain of the face plies; (3) working stresses for extreme fiber in bending as measured by a static bending test; (4) resisting momen and (5) shear strength.

This report, directed principally to designers and engineers, describes how the above strength and mechanical properties were determined for COM-PLY studs. These properties are related to the modulus of elasticity (MOE) of the veneer layers and the particleboard core. Such information may also help manufacturers to design COM-PLY studs whose strength properties differ slightly from those of the studs tested for this report.

MATERIALS

We needed a sample of COM-PLY studs for testing. To relate MOE of the stud components to the physical properties of assembled COM-PLY studs, we had to determine the MOE of the components before the studs were fabricated. On the basis of previous tests (Wittenberg 1977), we decided that a minimum of 10 COM-PLY studs would be required to provide a reasonable estimate of average MOE values. From sheets of slash pine veneer 1/6 inch thick, 26 inches wide, and 100 inches long, we ripped 52 strips 1-1/2 inches wide. These strips were trimmed to a length of 96 inches. All of the veneer had been conditioned to equilibrium moisture content (EMC) at 70° F and 40 percent relative humidity.

We used the stress-wave method of determining dynamic modulus of elasticity (MOE_d) for each strip. This method has been described by Koch and Woodson (1968). The veneer MOE_d value was used in all calculations and regressions.

The core material used in this study was a phenolic-bonded particleboard 1-1/2 inches thick. Twelve core strips were ripsawn from sheets to a width of 2.83 inches. The particleboard had an average density of 40 lb/ft^3, an internal bond of 75 lb/in^2, an MOE (in plane of panel) of 300,000 lb/in^2, and contained 8 percent phenolic resin binder throughout the three layers.

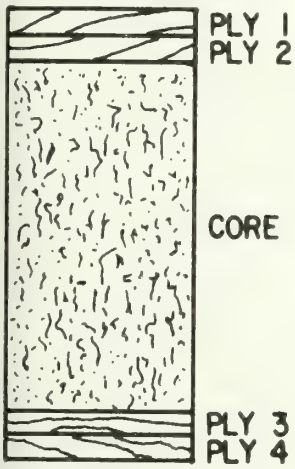
The face veneers of each stud were perpendicular to the plane of the panel from which the particleboard core was cut. We determined the MOE of the core in this orientation by center-loading the core as a simple beam over a span of 90 inches. Deflections at midspan were measured to the nearest 0.001 inch for loads of 10, 20, and 30 pounds. We used a dial gage mounted on a yoke to measure the deflections. To calculate the MOE in bending (MOE_b), we subtracted the

eflection at 10 pounds of load from the deflection at 30 pounds of load and etermined the slope of the load deflection curve for this 20-pound increment.

We also measured the MOE_d of the particleboard core with the stress-wave echnique. Results of this approach were erratic, however, and the MOE_b of the ore was used in all calculations.

We randomly selected four veneer strips for each core by drawing numbered ubes from a container. The order of selection was noted so that the first strip elected would be ply 1 in the completed stud, the second strip would be ply 2, nd so on. Figure 2 shows the arrangement of the plies.

The gluing procedures used in fabricating the COM-PLY studs had proved satisactory in previous studies (Vick 1977). After fabrication, each 96-inch-long stud as cut into segments for the four strength tests, as shown in figure 3.



gure 2.--Arrangement of veneer plies in the tested COM-PLY studs.

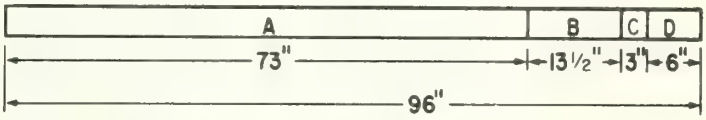


Figure 3.--Location of stud segments for the four strength tests: A, static bending; B, compression parallel to the grain; C, shear; D, compression perpendicular to the grain.

CALCULATION OF PROPERTIES OF TRANSFORMED SECTIONS

In any structural member, the section properties of most interest to engineers d designers are moment of inertia (I), section modulus (S), and area (A). For lid wood, the usual methods of calculating these properties are based on the asmption that the specimen is homogeneous and has constant dimensions. In comsite lumber, however, the veneer and particleboard components have different E's. The veneer MOE is about six to eight times as great as that of particleard. The section properties for composite materials are calculated by the method transformed sections. With this method, a member made up of materials with fferent MOE's is transformed into a member with one MOE. The well-known theories elasticity for strength of materials may then be applied to the member with acrate results. To transform a member made of materials with two MOE values, the tio of the MOE of the two materials must first be computed. If the lower MOE is vided by the higher MOE (the method used in this report), then the width of the terial with the lower MOE is reduced by the amount of the MOE ratio. This process ansforms the member into a cross-section having an MOE equal to that of the terial with the higher MOE (Higdon and others 1968).

A previous study of COM-PLY studs (Wittenberg 1977) indicated that the best estimate of stiffness was obtained from the average elastic modulus of the veneer plies. The method we used to compute the transformed section was based on this work. The approach is illustrated by the I-beam transformed section in figure 4.

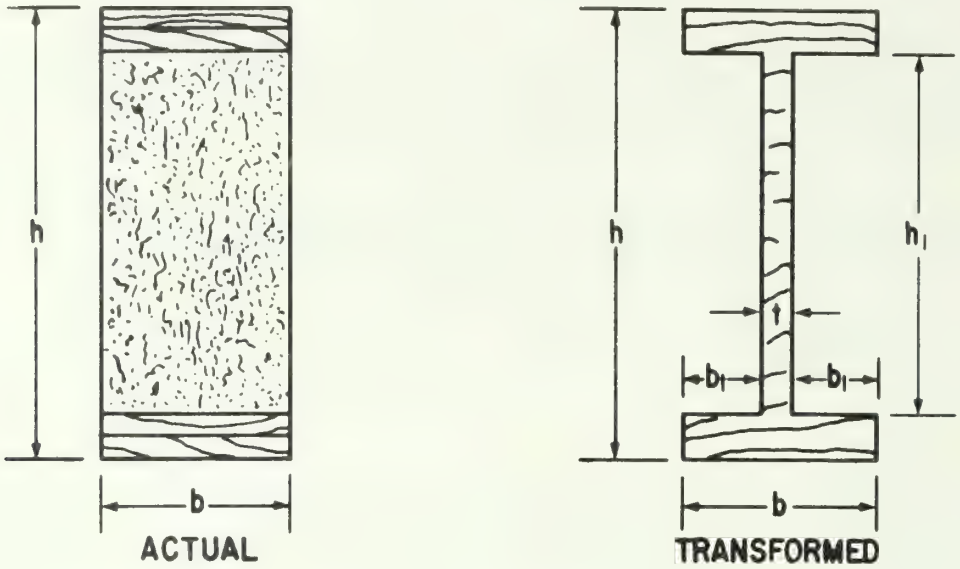


Figure 4.--Actual and transformed sections of a COM-PLY 2 x 4: h, height; b, flange width; h_1, core height; b_1, flange leg; t, transformed thickness.

The method is best illustrated by an example. Let us assume that the width of the composite lumber section is 1.5 inches and the height (h) is 3.5 inches. core height (h_1) is 2.83 inches. The average elastic modulus of the veneer strip is 2 x 10^6 lb/in^2, and the elastic modulus of the particleboard core is 0.25 x 10 lb/in^2. The thickness of the particleboard will be decreased by the ratio of the average MOE of the veneer to the average MOE of the particleboard. Thus,

$$\text{transformed thickness (t)} = \frac{\text{MOE particleboard}}{\text{MOE veneer}} \times 1.5 = \frac{0.25 \times 10^6}{2.0 \times 10^6}(1.5) = 0.1875 \text{ inch}$$

$$\text{and flange leg } (b_1) = \frac{1.5 - 0.1875}{2} = 0.656 \text{ inch}$$

The transformed section properties are calculated as follows:

$$\text{I (transformed)} = I_t = \frac{bh^3}{12} - 2\left(\frac{b_1(h_1)^3}{12}\right) = 2.88 \text{ in}^4$$

$$\text{S (transformed)} = I/c = 1.65 \text{ in}^3 \text{ (where } c = h/2)$$

$$\text{Area (transformed)} = A_t = bh - 2(b_1h_1) = 1.54 \text{ in}^2$$

The more complicated method of calculating transformed moment of inertia on the basis of area moment, as presented in texts on strength of materials, yields exactly the same results. In previous, unpublished studies, we calculated transformed moment of inertia for 30 COM-PLY studs by the area-moment method. In thos studies, we calculated a different MOE for each veneer ply, the average MOE of ea two-ply laminate, and the average MOE of all four plies. There was no statistica significant difference at the 5 percent level among the three methods. Therefore we decided to use the simplest one.

STATIC BENDING TEST

ETHODS

We performed the static bending tests according to the methods outlined in STM D 198-67 (ASTM 1975c). The test span was 69 inches with loads applied at ne-third points. The loads were applied with a universal testing machine. ead speed was maintained at 0.25 inch per minute. Height and width of the test egments were recorded to the nearest 0.001 inch. Deflections under load were etermined by using a dial gage mounted on a yoke, and readings were taken until he deflection was at least 0.500 inch. Then the gage and yoke were removed, nd the test was continued until failure. We recorded the time required to load he specimen to failure, the method of failure, and the maximum load.

To calculate the bending stiffness (EI_b) of the 12 COM-PLY studs, we subracted the deflection at 100 pounds of load from the deflection at 300 pounds of oad and calculated the slope of the load/deflection curve for the resulting 200-ound increment.

ESULTS

The results of the static bending tests for the sample of 12 COM-PLY studs re shown in table 1. The transformed moment of inertia (I_t) for the COM-PLY studs veraged 2.75 in^4. Standard wood studs measuring 1.5 by 3.5 inches would have a oment of inertia (I) of 5.36 in^4. The transformed section modulus (S_t) of the OM-PLY studs averaged 1.58 in^3 as compared to 3.06 in^3 for studs of solid wood. he comparable values for transformed area (A_t) were 1.39 in^2 and 5.25 in^2.

The smaller values for the properties of the transformed section would be ffset by higher values for allowable stress of the laminated veneers. Strength-imiting defects such as knots and cross-grain are less likely to be concentrated t a given cross-section in the laminated veneers than in studs of solid wood. herefore, COM-PLY studs are strong enough for use in residential construction.

The best predictor of actual bending stiffness (EI_b) for the COM-PLY studs as the average MOE_d of the four plies of veneer. The linear regression

$$EI_b = 2.43 + 1.53 \text{ x (average veneer } MOE_d)$$

ith all moduli in million lb/in^2 had a coefficient of determination (r^2) of 0.74. he bending stiffness of the COM-PLY studs was highly dependent on the MOE of the eneer edges. There was little linear correlation between bending stiffness and ther independent variables such as veneer thickness and particleboard MOE. The odulus of rupture (MOR) for the COM-PLY studs was also closely correlated with verage veneer MOE_d. The linear regression

$$MOR = -3811 + 0.005 \text{ x (average veneer } MOE_d)$$

d an r^2 of 0.73. These relationships are extremely important. If the average eneer MOE_d is known, then the bending properties of COM-PLY studs can be predicted with reasonable accuracy.

Table 1.--Results of static bending tests of a sample of 12 COM-PLY studs as based on transformed section analysis

Stud No.	Average veneer MOE_d	Core MOE_b	Properties of transformed sections			Bending stiffness EI		Ultimate load	Maximum moment (M max)	Maximum fiber stress (MOR)
			Moment of inertia (I_t)	Section modulus (S_t)	Area (A_t)	Actual	Predicted[1/]			
	Million lb/in^2		In^4	In^3	In^2	Million lb/in^2		Lb	In-lb	Lb/in^2
1	2.90	0.25	2.695	1.557	1.357	6.90	7.82	1,560	17,910	11,524
2	2.45	.23	2.983	1.696	1.477	5.77	7.31	1,435	16,502	9,730
3	2.42	.20	2.700	1.556	1.342	6.41	6.53	1,445	16,618	10,678
4	2.11	.22	2.964	1.684	1.502	5.63	6.25	915	10,522	6,247
5	2.63	.25	2.746	1.579	1.398	6.41	7.22	1,420	16,330	10,342
6	2.42	.23	2.753	1.584	1.397	6.01	6.66	1,165	13,398	8,459
7	2.71	.23	2.673	1.539	1.336	6.34	7.24	1,450	16,675	10,832
8	2.44	.23	2.726	1.568	1.390	6.63	6.65	1,055	12,132	7,737
9	2.12	.20	2.662	1.536	1.356	5.45	5.64	985	11,328	7,374
10	2.66	.25	2.795	1.602	1.412	6.78	7.43	1,465	16,848	10,515
11	3.03	.25	2.598	1.504	1.306	6.90	7.87	1,445	16,618	11,048
12	2.58	.26	2.679	1.550	1.397	6.41	6.91	1,400	16,100	10,384
Avg.	2.54	.23	2.748	1.580	1.389	6.30	6.96	1,312	15,084	9,573
SD	.275	.021	.117	.057	.057	.49	.65	219	2,515	1,691

[1/] $(EI_b)_p$ = (Average veneer MOE_d) x (I_t).

The allowable bending stress and safe resisting moment in bending were calculated by a formula similar to that proposed in ASTM D 245-74 (ASTM 1975a):

$$\text{Allowable strength property} = \frac{\text{Average ultimate strength} - t_{0.05}\ (\text{standard deviation})}{2.1^{1/}}$$

where $t_{0.05} = 1.796$ for 11 degrees of freedom. A more conservative approach to establishing allowable stresses can be found in ASTM D 2915-74 (ASTM 1975b). The COM-PLY studs used in this study were made from slash pine (*Pinus elliottii* Engelm.) veneer with an average MOE_d of 2.5×10^6 lb/in^2. They were not necessarily similar to COM-PLY studs made from other species. The allowable stresses presented below apply only to COM-PLY studs made from materials with properties similar to those of slash pine:

Average EI	Allowable fiber stress	Safe resisting moment
(Lb/in^2)	(Lb/in^2)	(In-lb)
6.30×10^6	3,112	5,032

TEST OF COMPRESSION PARALLEL TO THE GRAIN

METHODS

A strength property of interest to engineers and designers is compression strength parallel to the long axis of the stud. Axial loading simulates the use of the stud as a column to carry compressive loads.

The test procedure we used to test compression parallel to the veneer grain was based on the recommendation in ASTM D 198-67 for short columns (ASTM 1975c). Load was applied through a spherical loading head on a universal testing machine. We recorded deflections over a 6-inch gage length (to the nearest 0.0001 inch) for each 1,000-pound load increment until the COM-PLY segment failed.

The load/deflection curve for each segment was plotted on graph paper so that the load at the proportional limit could be determined. For each segment, we recorded ultimate load, the time needed to apply that load, and the weight of the segment. All dimensions were measured to the nearest 0.001 inch. The test setup is shown in figure 5.

RESULTS

The results of the tests on compressive load are shown in table 2. The average compressive strength (ultimate stress) for the COM-PLY studs was 8,577 lb/in^2 (A_t basis)--approximately the 8,140-lb/in^2 value published for slash pine (USDA 1974). The best predictor of the modulus of elasticity in compression was the average veneer MOE_d with an r^2 of 0.625. The average compressive MOE was 3.91×10^6 lb/in^2 as based on the transformed area. This value is very high. A larger sample might confirm this value and offer some explanation for the difference between bending and compressive MOE's.

1/ The safety factors differ for various strength properties. Consult ASTM D 245-74 (ASTM 1975a, table 9).

The allowable compressive stress (f_c) for COM-PLY studs as calculated by the same basic formula (ASTM 1975a) used for bending stresses would be

$$f_c = \frac{8,577 - 1.796\ (1,145)}{1.9} = 3,432\ \text{lb/in}^2$$

The compression MOE was correlated with bending stiffness ($r^2 = 0.59$) and modulus of rupture ($r^2 = 0.50$). This relationship suggests that a compression test for short columns may be useful for quality control. Further work with samples made from a variety of core materials will be necessary to confirm these relationships.

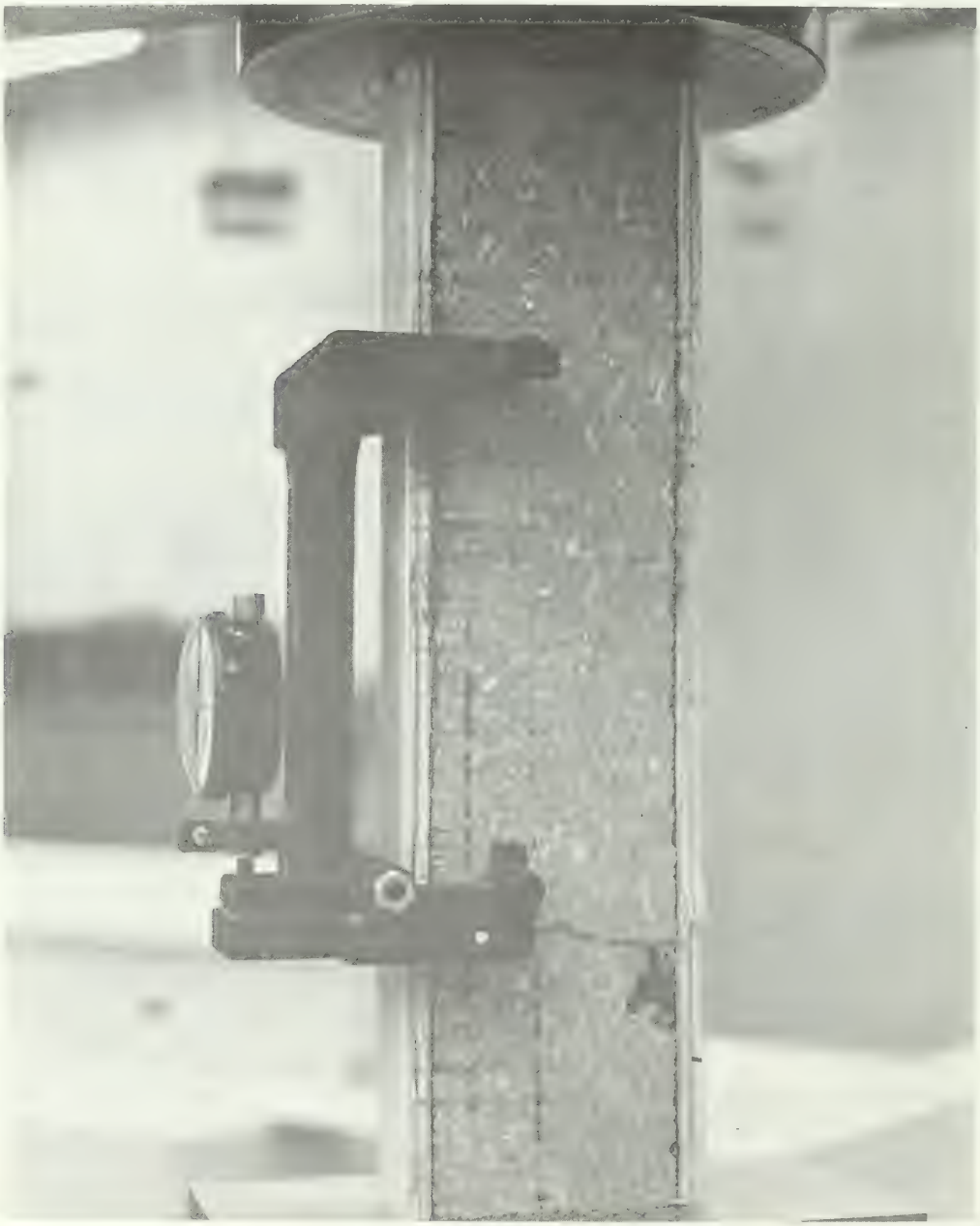


Figure 5.--Setup for testing compression parallel to the veneer grain.

Table 2.--Values of compressive-load strength for a sample of 12 COM-PLY studs as based on transformed areas

Stud No.	Load to proportional limit	Ultimate load	Stress at proportional limit	Ultimate stress	Compressive MOE
	---------Lb----------		------Lb/in^2-------		Million lb/in^2
1	8,000	12,640	5,896	9,316	6.32
2	8,000	10,500	5,415	7,108	3.38
3	7,000	10,680	5,215	7,957	4.06
4	7,500	10,540	4,994	7,018	2.85
5	5,000	11,080	3,576	7,924	3.58
6	7,000	11,540	5,009	8,258	3.30
7	6,000	13,020	4,492	9,748	3.74
8	8,500	11,880	6,115	8,457	3.60
9	6,000	10,920	4,424	8,052	3.16
10	8,000	11,600	5,666	8,216	4.25
11	8,000	13,680	6,127	10,477	5.11
12	11,500	14,400	8,229	10,304	3.58
Avg.	7,542	10,957	5,430	8,577	3.91
SD	1,630	3,147	1,160	1,145	.955

TEST OF COMPRESSION PERPENDICULAR TO THE GRAIN

ETHODS

The test for compression perpendicular to the veneer grain measures a stud's ɔility to resist crushing or bearing loads. Our test of this property was based ɲ the procedures outlined in ASTM D 143-52 (ASTM 1975d). Only the 1-1/2-inch-ide veneer edge was tested. The 3-1/2-inch-wide face was not uniform because ɲe veneer plies were not perfectly aligned with the core. Removing enough core ɑterial and veneer to provide flat, parallel surfaces would have given erroneous ɛst results.

The test was made on a universal testing machine with a capacity of 10,000 ɔunds. The test setup is shown in figure 6. Head speed was 0.01 inch per minute. ɛ measured the deflection of the 2-inch-wide loading block (to the nearest 0.0001 ɲch) for each 200-pound load increment until the total deflection reached 0.10 ɲch. We considered that the 0.10-inch deflection constituted failure. This load ɑs recorded as maximum load.

The load/deflection curve was plotted on graph paper so that the load at the ɾoportional limit could be determined. For each segment, we recorded the weight, ll dimensions to the nearest 0.001 inch, the identification number of the outer ɛneer ply under the loading block, and the time needed to reach a deflection of .10 inch.

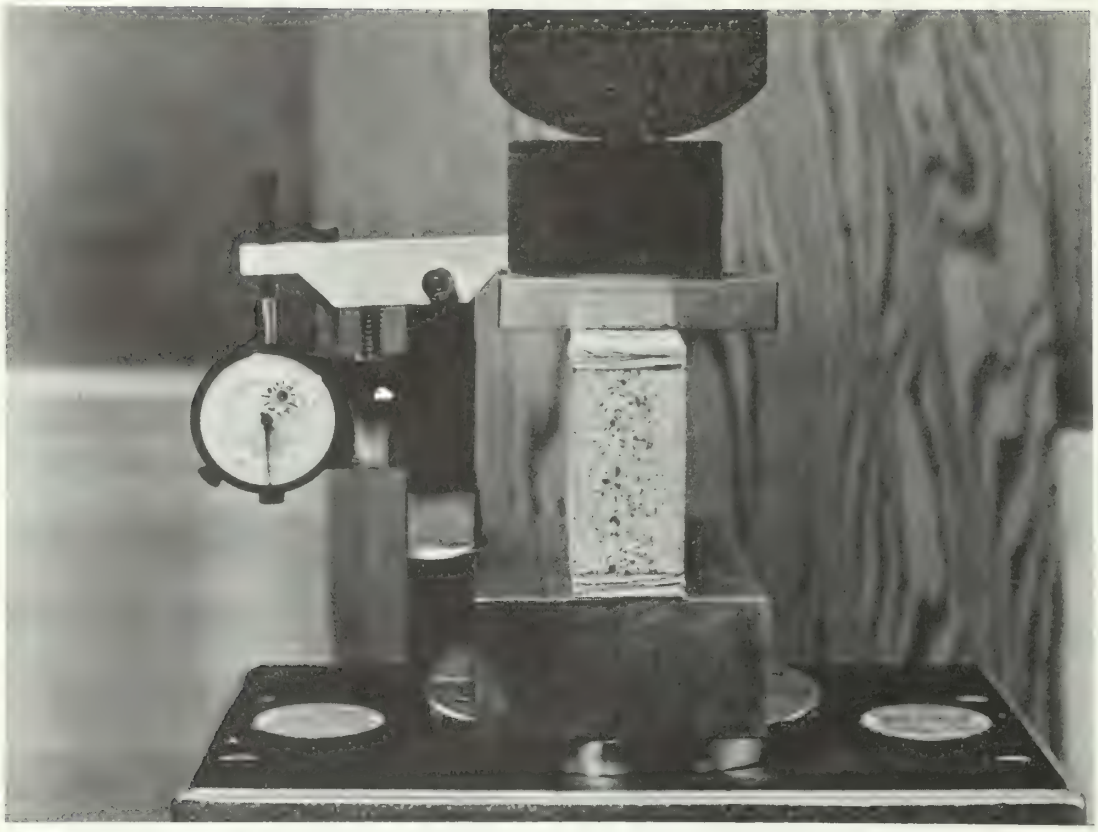


Figure 6.--Loading arrangement for testing compression perpendicular to the veneer grain.

RESULTS

Results of these tests are shown in table 3. The average fiber stress at the proportional limit was 572 lb/in^2. The allowable bearing stress calculated by the same basic formula (ASTM 1975a) used for bending stress would be

$$\text{Allowable bearing stress} = \frac{571.9 - 1.796\ (128.9)}{1.5} = 227\ \text{lb/in}^2$$

This value is less than that published for southern pine but is about the same as those for spruce and Hem-fir stud grades. The stress distribution for compressio loading of the veneer edges was unusual because of the composite construction. Most of the samples failed, as shown in figure 7. Any change in the properties of the components would greatly affect values for compression perpendicular to the veneer face.

Table 3.--Values of compression perpendicular to the veneer face for a sample of 12 COM-PLY studs

Stud No.	Core bending MOE	MOE_d of face ply	Load at proportional limit	Load at 0.10-inch compression	Stress at proportional limit	Stress at maximum load
	Million lb/in^2		--------Lb---------		-----Lb/in^2------	
1	0.25	2.92	2,000	5,050	646	1,631
2	.23	3.22	1,600	4,450	529	1,472
3	.20	2.73	1,800	3,870	591	1,270
4	.22	2.07	1,400	3,290	457	1,074
5	.25	1.89	1,800	3,400	587	1,108
6	.23	2.78	1,200	3,180	393	1,041
7	.23	2.40	2,200	4,420	723	1,453
8	.23	2.25	2,400	4,720	789	1,552
9	.20	2.28	1,200	3,310	389	1,073
10	.25	3.16	2,000	3,500	654	1,145
11	.25	3.27	2,000	4,280	649	1,390
12	.26	2.40	1,400	3,375	456	1,099
Avg.	.23	2.61	1,750	3,904	572	1,276
SD	.021	.465	392	649	129	213

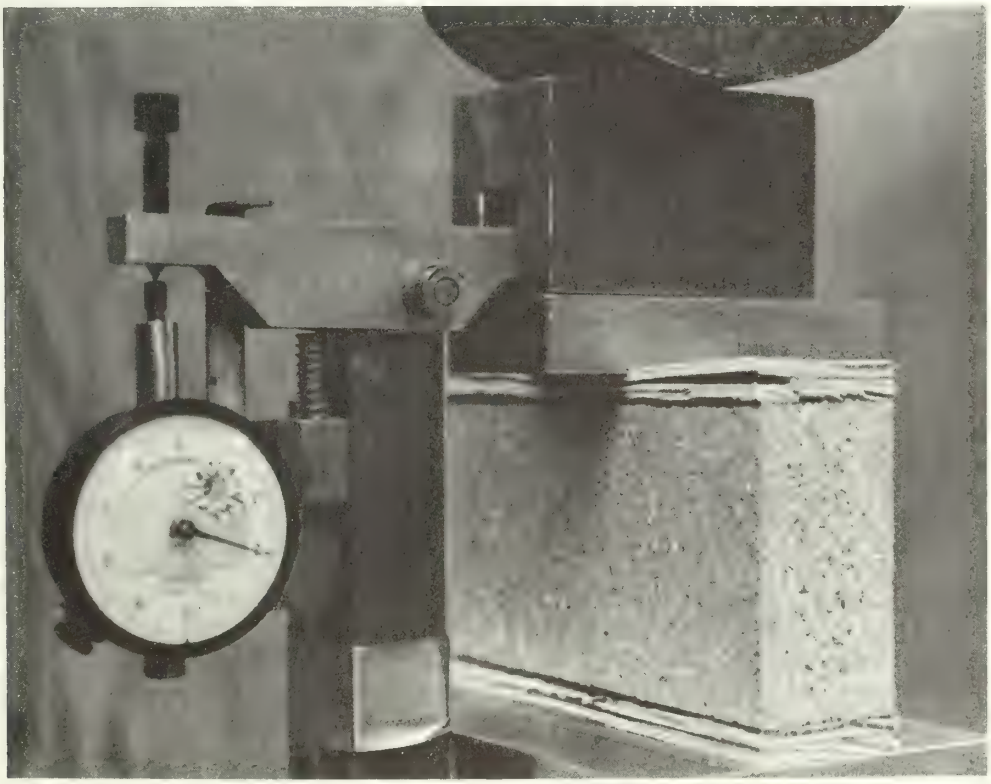


Figure 7.--Typical method of failure for COM-PLY studs tested in compression perpendicular to the grain of the veneer edges.

METHODS

In COM-PLY studs, the greatest shear stresses are likely to occur in the particleboard core. Accordingly, our shear tests were made on the particleboard in a plane perpendicular to the plane of the particleboard faces. We used a test procedure adapted from ASTM D 143-52 (ASTM 1975d). The configuration of the shear specimen finally selected after extensive preliminary trials is shown in figure 8.

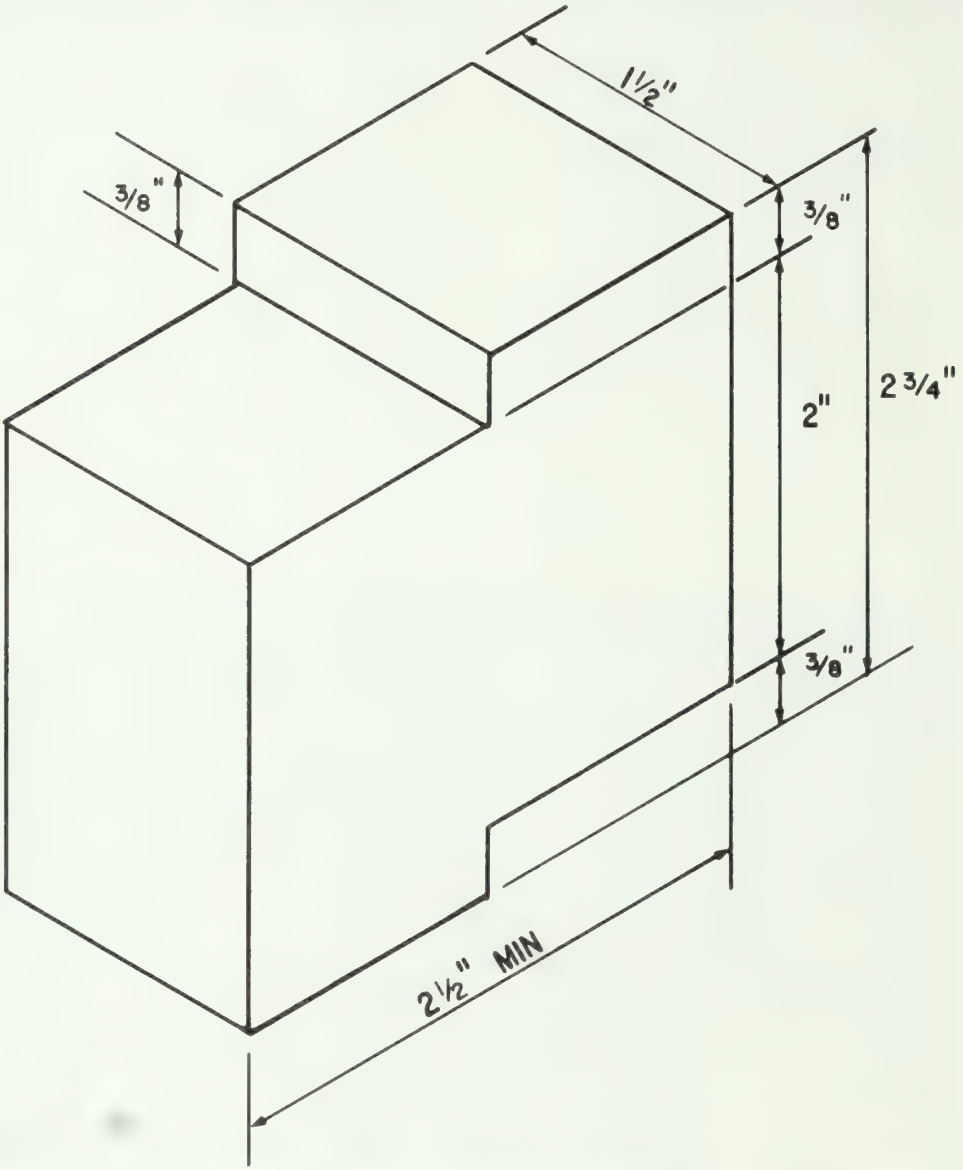


Figure 8.--Test specimen for horizontal shear test of COM-PLY studs.

The veneer edges were removed to permit accurate sawing of the shear specimen. The double-step cut was required to keep the shear specimen from tipping. We also found that the shear tool had to be set up without the 1/8-inch offset specified in ASTM D 143-52 (ASTM 1975d) for shear tests of solid wood blocks.

The shear tests were run on a universal testing machine with a capacity of 10,000 pounds. Head speed was 0.02 inch per minute. For each segment, we recorded the weight and maximum load to failure.

RESULTS

The results of the shear test are shown in table 4. The allowable shear stress calculated by the same basic formula (ASTM 1975a) used for other strength properties would be

$$\text{Allowable shear stress} = \frac{873 - 1.796\ (128)}{4.5} = 143\ \text{lb/in}^2$$

Obviously, any change in the components of the particleboard would affect the shear value.

Shear in the plane tested here is not usually determined for particleboard. Shear values were correlated with values for MOE_b of the particleboard core ($r^2 = 0.57$). Most of the shear samples failed in a plane about 30° from the vertical, as shown in figure 9.

Table 4.--Results of horizontal shear test of particleboard cores from 12 COM-PLY studs tested in a plane parallel to the plane of the veneer faces

Stud No.	Particleboard bending MOE	Load at proportional limit	Maximum load	Stress at proportional limit	Maximum shearing stress
	Million lb/in^2	--------Lb---------		-----Lb/in^2------	
1	0.25	2,000	2,780	667	927
2	.23	1,600	2,635	533	878
3	.20	1,000	2,345	333	782
4	.22	1,750	2,550	583	850
5	.25	2,050	2,900	683	967
6	.23	1,650	2,655	550	885
7	.23	1,000	2,000	333	667
8	.23	1,600	2,590	533	863
9	.20	1,300	2,100	433	700
10	.25	1,600	2,485	533	828
11	.25	1,950	2,975	650	992
12	.26	2,200	3,420	733	1,140
Avg.	.23	1,642	2,620	547	873
SD	.021	388	384	129	128

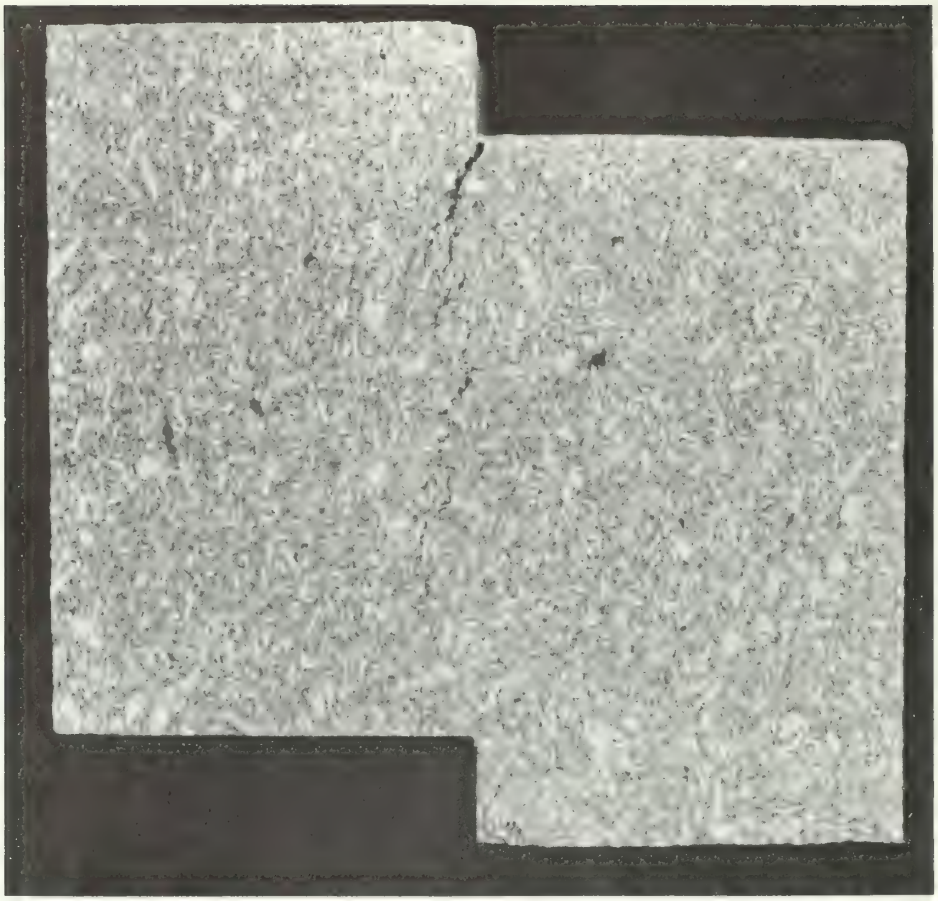


Figure 9.--Typical mode of failure in particleboard specimens subjected to the shear test.

CONCLUSIONS

These and other bending tests of COM-PLY studs (Wittenberg 1977) show that the average MOE_d of the veneer component is the best single predictor of most strength properties. The bending stiffness (EI) and MOR have linear regressions with $r^2 > 0.70$. The compressive MOE and ultimate compressive stress were also well correlated with average veneer MOE_d.

Consequently, potential manufacturers of COM-PLY studs need extensive information on the MOE_d of available veneer supplies. Such information will enable them to determine the veneer thickness that will be most efficient in terms of designing studs to meet Performance Standards. The stress-wave method used in these tests offers a fast, reliable, non-destructive method of determinin veneer MOE_d.

The method of computing transformed sections used in this study gives reason able correlation with test results. Further work with larger sample sizes is needed to establish better mathematical models of the relationship between component MOE's and composite strength properties.

The allowable stress values reported in this study are based on a limited sample made with controlled glue spreads and assembly conditions; the veneer was

of exceptional quality. The allowable stresses reported are not intended as typical design values for all COM-PLY studs, but they will serve as a guide to others interested in the strength properties of COM-PLY studs.

The methods used in these calculations are valid and offer manufacturers a way to determine allowable stresses for COM-PLY studs of specific designs.

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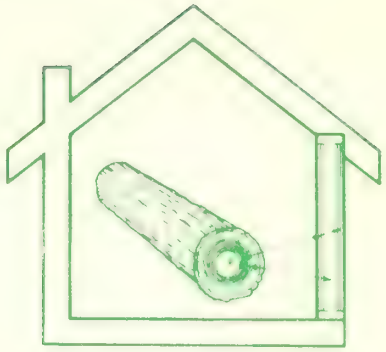

COM-PLY REPORT 13

STRUCTURAL PERFORMANCE AND STANDARDS FOR COMPLY PARTITION STUDS

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COOPERATIVE RESEARCH

May 1978

Southeastern Forest Experiment Station
Asheville, North Carolina

STRUCTURAL PERFORMANCE AND STANDARDS FOR COM-PLY PARTITION STUDS

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Cooperative Research by

U.S. Department of Agriculture, Forest Service

Southeastern Forest Experiment Station

and

U.S. Department of Housing and Urban Development

Division of Energy,

Building Technology and Standards

PREFACE

This report is one of a series on the possibilities of producing house framing and structural panels with particleboard cores and veneer facings. The COM-PLY or composite materials were designed to be used interchangeably with conventional lumber and plywood in homes. Research on structural framing is presently limited to COM-PLY studs but will be extended to include larger members such as floor joists.

In 1973, the home-building industry faced a shortage of lumber and plywood and consequent rising prices. Both industry and government recognized that this situation was not a temporary problem, and that long-range plans for better using the Nation's available forest resources would be necessary.

The USDA Forest Service and the U.S. Department of Housing and Urban Development accelerated cooperative research on ways to utilize the whole tree. They concentrated on composite wood products made with particleboard and veneer as a way of using not only more of the tree stem, but also using less desirable trees and a greater variety of tree species than would conventional wood products. The particleboard which comprises a large portion of the COM-PLY stud is made from chipped-up wood that comes from forest residues, mill residues, or low-quality timber. Thus, such composites could greatly increase the amount of lumber and plywood available for residential construction, our major use of wood, without eroding the Nation's timber supply.

Research on composite wall framing was performed by the Wood Products Research Unit, Southeastern Forest Experiment Station, Athens, Georgia. The American Plywood Association cooperated in these studies by designing and testing composite panel products that are interchangeable with plywood. Both types of products have been incorporated in demonstration houses.

Included in this series will be reports on structural properties, durability, dimensional stability, strength, and stiffness of composite studs. Other reports will describe the overall project, compare the strength of composite and solid wood studs, suggest performance standards for composite studs, and provide construction details on houses incorporating such studs. Still others will explore the economic feasibility of manufacturing composite studs and panels and estimate the amount and quality of veneer available from southern pines. These reports, called the COM-PLY series, will be available from the Southeastern Forest Experiment Station and the U.S. Department of Housing and Urban Development.

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National Particleboard Association

STRUCTURAL PERFORMANCE AND STANDARDS FOR COM-PLY PARTITION STUDS

Abstract.--COM-PLY partition studs made with two plies of 1/8-inch-thick southern pine veneer on each 1-1/2-inch face of a particleboard core of medium density are strong and stiff enough for use in interior nonload-bearing partitions in houses. These 2- x 3-inch partition studs can be used as a direct substitute for conventional 2- x 3-inch lumber studs and at the same spacings. Stiffness rather than strength controlled the design of COM-PLY partition studs.

KEYWORDS: Composite lumber, wood veneer, particleboard, southern pine, sandwich construction, structural sandwich.

A new composite lumber product has been developed through cooperative research by the U.S. Department of Housing and Urban Development and the USDA Forest Service. The new product, called COM-PLY, has potential for significantly increasing the supply of lumber for homes. Less than half as many trees are required to produce COM-PLY lumber as for the same amount of conventional lumber.

Constructed as a structural sandwich, COM-PLY has a particleboard core placed between layers of solid wood veneers. The particleboard cores of COM-PLY studs are made from chipped-up wood taken from forest residues, mill residues, or low-quality timber. In this report, COM-PLY lumber refers to 2 x 3 studs (fig. 1) typically used to frame nonload-bearing, interior partitions in houses. COM-PLY partition studs are to be used as direct substitutes for conventional 2 x 3 lumber studs and at the same spacings.

Figure 1.--COM-PLY stud used for framing interior partitions in houses.

Potential manufacturers, building code officials, and builders must be able to determine the structural strength and stiffness of COM-PLY studs to ensure that they are safe and acceptable for use in homes. This report presents suggested standards of structural performance for COM-PLY 2 x 3 studs used for partitions in homes and the results of structural tests on a limited number of such studs fabricated in the Forestry Sciences Laboratory at Athens, Ga.

Performance standards for durability, dimensional stability, and nailed joint strength are not covered in this report. Guidelines for evaluating these properties can be found in "Performance Standards for Composite Studs Used in Exterior Walls" (Blomquist and others 1976). However, before durability or strength of nailed joints can be determined for partition studs, the levels of strength and stiffness as specified in the Performance Standard for studs in exterior walls must be reduced to the lower levels set forth in the present report. Because the size and spacing of nonload-bearing studs for interior partitions are generally based on bending strength and stiffness, axial compressive end loads need not be applied to partition studs during tests of structural performance.

METHODS OF EVALUATING STRUCTURAL PERFORMANCE

BACKGROUND ON PERFORMANCE REQUIREMENTS

Because building code officials do not know the type of facing that a builder will choose nor how he will install it, they usually assume that the facing used will not increase the strength and stiffness of the studs in interior partitions. Gypsum wallboard is the typical facing used in residential construction.

There are nearly 30 species-grade combinations listed as stud-grade in the "National Design Specifications for Stress-Grade Lumber and Its Fastenings" (NFPA 1973). The modulus of elasticity (MOE) varies from 600,000 lb/in^2 for northern white-cedar to 1,500,000 lb/in^2 for Douglas-fir and larch. The allowable bending stress when loads are shared with adjacent members varies from 450 lb/in^2 for black cottonwood to 950 lb/in^2 for southern pine. These are values for 2 x 4, exterior, load-bearing wall studs and do not necessarily reflect the values required for 2 x 3, interior, nonload-bearing studs. They are also average values. Consequently, we would expect some 2 x 4's of solid wood to have only half the published values for average strength and stiffness and others to have as much as twice these values.

STRUCTURAL PERFORMANCE REQUIRED FOR COM-PLY PARTITION STUDS

The species of wood in greatest supply and, thus, most widely used for studs in interior partitions have higher than average values for strength and stiffness. For stud-grade material, stiffness probably ranges between 1,000,000 and 1,500,000 lb/in^2 in typical houses, while the allowable bending stress with shared loads probably ranges between 725 and 950 lb/in^2. Composite studs having average strength and stiffness at the lower ends of these ranges would probably be acceptable because they have less variability in the two properties than do studs of sawn lumber. Such COM-PLY studs would be far stronger and stiffer than most grades of solid studs having the minimum strength and stiffness allowable under the "National Design Specification for Stress-Grade Lumber and Its Fastenings" (NFPA 1973).

According to this reasoning, a composite stud used for nonload-bearing, interior partitions should have stiffness equivalent to that of a stud with an average MOE of approximately 1,000,000 lb/in^2. Approximate strength of the composite should be equivalent to that of a stud with a bending stress of 725 lb/in^2. Composite studs must have this strength and stiffness if they are to be directly substituted for typical 2 x 3 studs spaced 24 inches on center. Stiffness is a

product of the MOE and the moment of inertia, whereas strength is the product of the bending stress and the section modulus. The strength must account for duration of loading and a factor of safety. The moment of inertia for a 2 x 3 stud is 1.95 in^4, and the section modulus is 1.56 in^3. The average acceptable stiffness (EI) for a 2 x 3 composite stud should be approximately 1,000,000 lb/in^2 x 1.95 in^4 or 1,950,000 $lb\text{-}in^2$. The average acceptable strength for a 2 x 3 composite stud should be approximately 725 lb/in^2 x 1.56 in^3; thus, average resisting moment would be 1,131 in-lb.

Engineers with the Technical Standards Division of the Federal Housing Administration (FHA) have set limits on bending deflection for partition studs under a uniformly distributed load. The limit is 1/240th of a bending span of 72 inches. Studs are normally 93 inches long, but these engineers consider the effective bending length to be 72 inches because of end fixity. The amount of end fixity is indeterminate, and providing semi-rigidity of the ends during testing would be impractical. Therefore, the studs are tested as a simply supported beam 72 inches long and without end fixity. For studs having an average stiffness of 1,950,000 $lb\text{-}in^2$ and spaced 2 feet on center, a load of 10 lb/ft^2 (20 lb/linear ft) comes close to causing the maximum bending deflection that the FHA Engineers have set for partition studs.

To compute the acceptable stiffness of COM-PLY partition studs, use a deflection limit of 1/240th of a 72-inch test span with a load of 20 lb/linear ft uniformly distributed along the length of the stud.

TESTING STRUCTURAL PERFORMANCE

General

Test the studs under a transverse bending load. The bending load is assumed to be a uniformly distributed load acting in the 2-1/2-inch direction of the stud, along its entire length. To simplify the test procedure, use two concentrated loads placed at quarter points of the bending span. In this case, the two concentrated loads will impose the same bending moment at midspan of the stud as if the same load were uniformly distributed along the stud's length. The maximum moment from two concentrated loads is continuous over the middle half of the stud, whereas a uniformly distributed load places the maximum moment only at midspan. Therefore, a standard based on the application of concentrated loads is somewhat conservative. A beam bent by two concentrated loads at the quarter points will deflect 1.1 times as much at midspan as a beam bent by a uniformly distributed load of the same amount. Since the standard calls for two concentrated loads, the increased deflection must be accounted for. As noted previously, the standard deflection under a uniformly distributed load is 1/240th of the span in inches. A uniformly distributed bending load of 20 lb/linear ft will place 120 lb of bending load on a 72-inch test span and deflect the beam 0.30 inch. However, two concentrated bending loads totaling 120 lb (60 lb each) on a 72-inch test span will deflect the same beam 0.33 inch. These minimum levels of structural performance have apparently been satisfactory for housing insured by FHA.

Test Apparatus

The test span and apparatus generally conform with the requirements set forth in ASTM Standard D 198-67 (ASTM 1975c). In setting up the testing apparatus (fig. 2), rest the stud on rocker supports to resist bending reactions over a test span of 72 inches.

The two concentrated loads are applied to the specimen at quarter points through curved loading blocks which bear across the entire width of the specimen.

The loads are applied through a system of rollers to assure uniform distribution and to avoid introducing secondary stresses in the specimen as it deflects under test loading (fig. 3).

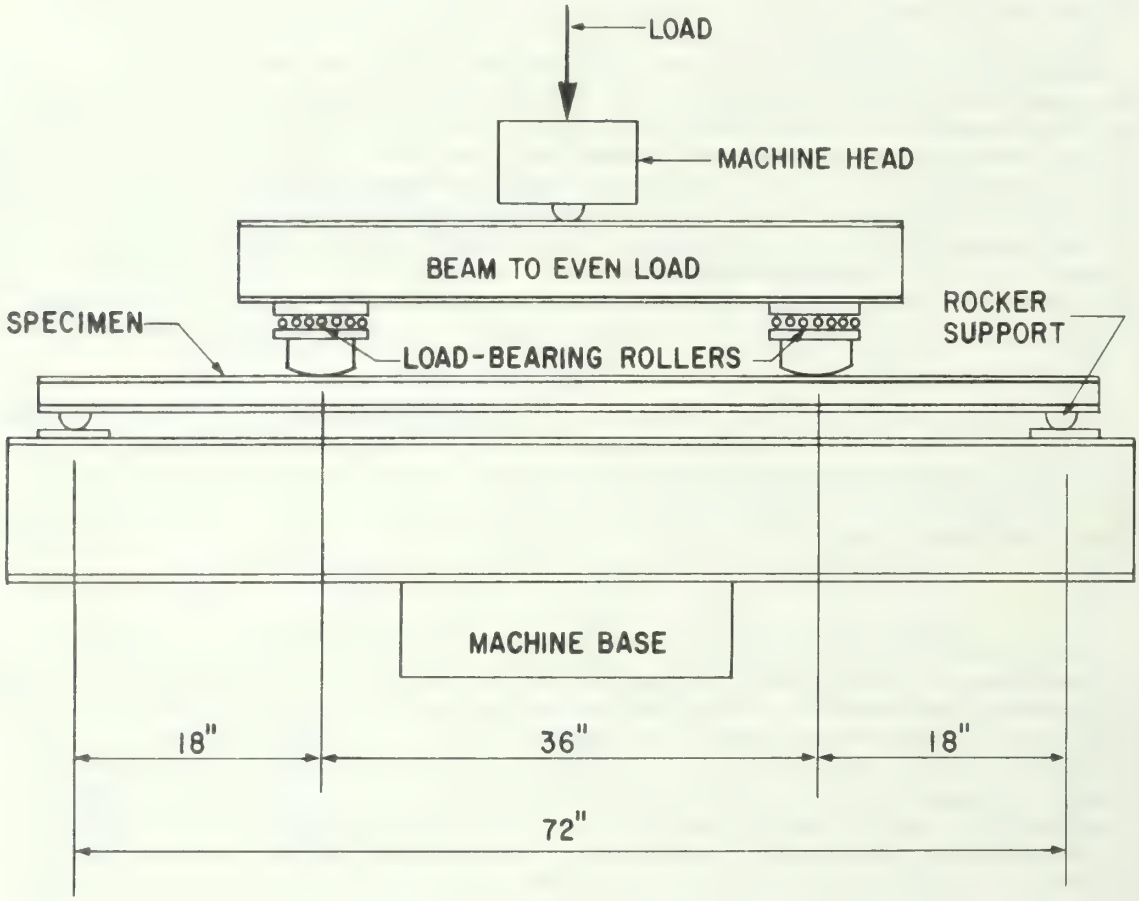

Figure 2.--Loading method for bending test.

Apply the loads with a universal testing machine that has been calibrated for accuracy according to the requirements of ASTM Methods E 4-72 (ASTM 1975d). The frame for the dial gage (fig. 4) is supported by nails driven into the side of the test stud at midheight, directly over the end points of the test span. This arrangement prevents the deflection readings from being affected by any settling of the supports.

Test Specimens

When possible, the manufacturer should provide the testing laboratory with the following information on the COM-PLY studs submitted:

-Thickness of veneers

-Species or combinations of species used for veneer

-Quality of veneer

-Type and spread rate of laminating adhesive

-Geometry of wood particles in the particleboard

-Percentage and type of particleboard binder

-Percentage and type of particleboard wax

-Internal bond of particleboard

-Density of particleboard

-Thickness swelling of particleboard

-Linear expansion of particleboard

-Modulus of elasticity of particleboard

-Modulus of rupture of particleboard

-Trademark identifying specifications to which COM-PLY studs were made

Properties of the particleboard core such as internal bond, density, thickness swelling, linear expansion, MOE, and modulus of rupture (MOR) should be determined by the methods set forth in ASTM Standard D 1037-72a (ASTM 1975b).

All specimens must be tested at a moisture content of 10 $\pm$ 2 percent. This content can be attained by conditioning studs to constant weight under controlled temperature and relative humidity: for example, $80^{\circ} \pm 6^{\circ}$ F ($27^{\circ} \pm 3^{\circ}$ C) and a relative humidity of 65 $\pm$ 1 percent, or an equivalent combination.

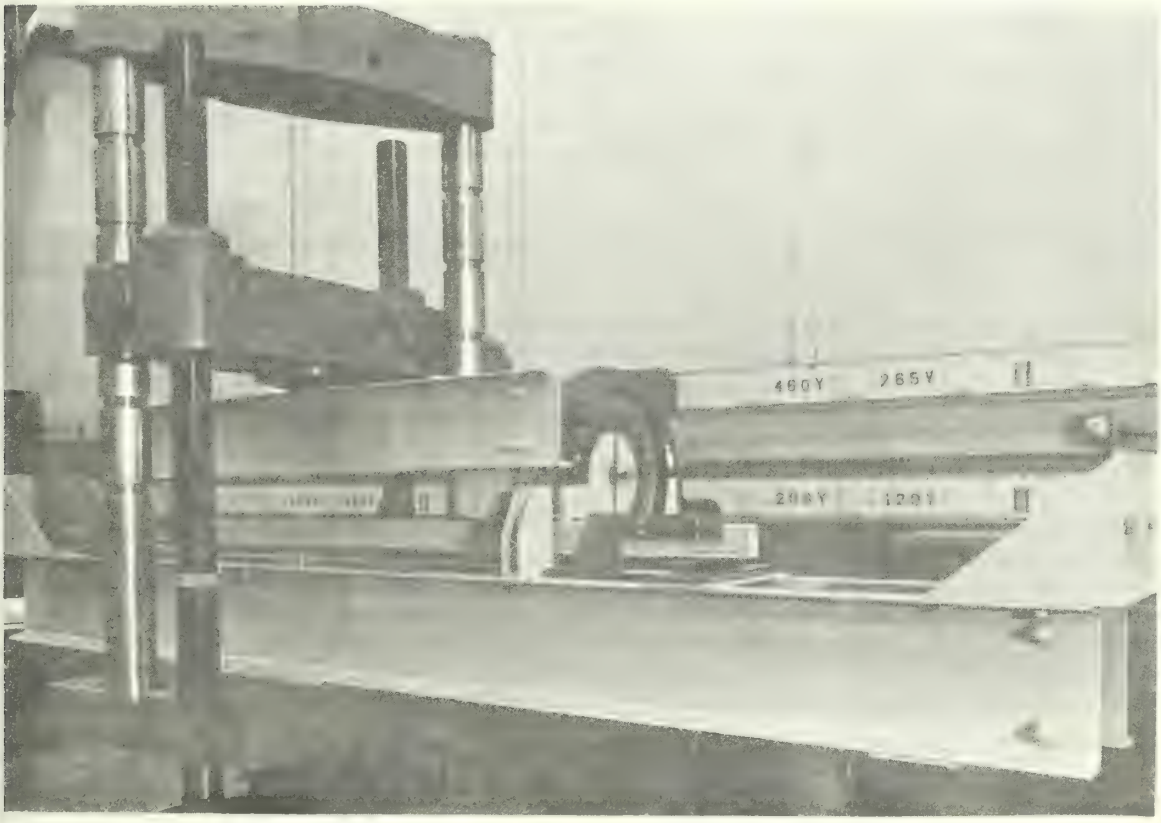

Figure 3.--COM-PLY 2 x 3 partition stud in universal testing machine ready for bending test.

Figure 4.--Dial gage mounted on frame with supports at ends of the specimen.

Test Procedure

Place the test specimen on the rocker supports and the gage frame on the nail supports. Record the initial gage reading before any bending load is applied to the test specimen other than its own weight. Bending deformation of the test specimen as a result of its dead weight need not be measured. In the test apparatus, laterally support the stud to prevent buckling under load. Apply continuously increasing bending load to the specimen at a constant rate (pounds per minute) or head speed (inches per minute) until ultimate load is reached and the specimen fails. Ultimate load or failure takes place when deformation occurs at an increasing rate per unit of time with no increase in load or when the test specimen has collapsed. Select a rate of load or head speed that will result in failures in not less than 6 nor more than 20 minutes. For specimens of average strength and stiffness, a rate of load of 45 pounds per minute or head speed of 0.2 inch per minute would be typical.

During loading to failure, read the gage and record deflection at sufficiently close intervals to plot a load-deformation curve. Load intervals of 50 to 80 pound are typical. Also record the deflection occurring when the bending load reaches 120 pounds.

Computing Adjusted Strength and Stiffness

Average ultimate test loads must be adjusted to determine the safe load a specific sample of COM-PLY partition studs might withstand. The adjustments are determined from statistical and empirical factors that account for variation in test values, speed of testing, load sharing, and safety. The formulas and factors for making the adjustments are described in the Performance Standards (Blomquist and others 1976). To determine the adjusted strength (W) of a sample of COM-PLY studs, use the following formula:

$$W = \left[\bar{w} - \frac{t_{0.05} S}{\sqrt{N}} - t_{0.05} S \right] \frac{F_r}{F_s F_t}$$

where:

W = adjusted value for load in pounds for two concentrated loads

$\bar{w}$ = average ultimate test load in pounds for two concentrated loads on a stud

$t_{0.05}$ = statistical t at 0.05 confidence level for N - 1 degrees of freedom

S = standard deviation of ultimate test loads in pounds for two concentrated loads

N = number of test specimens

F_r = allowable increase for load sharing among adjacent wall studs in typical wall framing; use 1.15

F_s = safety factor; use 1.5

F_t = adjustment for the ratio of the duration of the test load to the duration of the service load. In this case, the service load is assumed to be the wind load, and the factor for the duration of this load is 1.33. If the test load is applied over an average period of 15 minutes, the factor for the duration of this load is 1.57. In this example, the test load is applied faster than the service load; therefore, the adjustment factor is 1.57/1.33 or 1.18 (Hunt and others 1973; ASTM 1975a).

Next, compute the adjusted resisting moment (M) for the test sample of COM-PLY studs with the following formula:

$$M = \frac{W\ L}{8}$$

where:

M = adjusted resisting moment for the test sample of COM-PLY studs in inch-pounds

W = adjusted value for load in pounds for two concentrated loads

L = the test span in inches

If the value of M is greater than the standard level of 1,130 in-lb, the bending strength of the stud design is acceptable.

To determine if the adjusted stiffness of a sample of COM-PLY partition studs is acceptable, use the following formula:

$$D = \bar{d} + \frac{t_{0.05} S}{\sqrt{N}}$$

where:

D = adjusted value for midspan deflection in inches

$\bar{d}$ = the average midspan deflection of N test studs when two 60-pound concentrated loads are applied

$t_{0.05}$ = statistical t at 0.05 confidence level for N - 1 degrees of freedom

S = standard deviation of midspan deflections when two 60-pound concentrated loads are applied

N = number of specimens

The stiffness of the stud design is acceptable if the value for D is 0.33 inch or less. Studs meeting this criterion will have an average stiffness (EI) of about 1,900,000 lb-in^2. A stud with this stiffness will be satisfactory for use in homes, according to FHA Engineers.

A sample group of 10 studs is usually sufficient to evaluate the strength and stiffness of a given stud design. If this sample meets all the performance levels required, then the design is considered acceptable. If the results of any tests are slightly below the required level, then 10 additional specimens may be tested and the results averaged with those of the previous test. Such averaging may raise the test results to an acceptable level. There is seldom any advantage to testing more than 30 studs for a given property.

Test Report

After completing the tests, the laboratory should report the following information to the manufacturer:

- -Number of specimens tested in each evaluation
- -Test values for individual specimens
- -Average test values
- -Standard deviation of test values
- -Computation of adjusted values for the population of studs
- -Explanatory notes on any unusual modes of failures

LABORATORY TESTING OF COM-PLY PARTITION STUDS

MATERIALS

In the Athens laboratory, researchers fabricated two groups of COM-PLY 2 x 3 partition studs. On one group of 10 studs, they used 1/8-inch-thick veneers for facings; on the other group of 10 studs, they used 1/6-inch-thick veneers. All studs were 1-1/2 inches thick, 2-1/2 inches wide, and 96 inches long. Double layers of southern pine veneer were laminated to a core of particleboard, as shown in figure 5.

The 1/8-inch-thick veneer was loblolly pine (*Pinus taeda* L.) randomly selected from a study group of veneer at Birmingham Forest Products, Cordova, Ala. This veneer had an average dynamic MOE of 1.89×10^6 lb/in^2 as determined by stress-wave equipment. The 1/6-inch-thick veneer was loblolly pine obtained from the Southern Forest Experiment Station at Alexandria, La. This veneer had an average dynamic MOE of 1.81×10^6 lb/in^2.

The cores were cut from 1-1/2-inch-thick, commercially made particleboard. In making the particleboard, the manufacturer used an air suspension technique to separate wood particles into three layers during the mat-forming process. The particles were made from planer shavings, slabs, edgings, and other mill residues from southern pine. The particleboard had an average density of 40 lb/ft^3, an internal bond of 75 lb/in^2, a MOE of 300,000 lb/in^2 (in plane of panel), a MOR of 3,400 lb/in^2 (in plane of panel), and contained 8 percent phenolic-resin binder throughout.

Veneers were laminated to the particleboard cores with phenol-resorcinol, a laminating adhesive that cures at room temperature. The laminating adhesive was spread at a rate of 40 lb/Mft^2 of single glueline at the veneer-to-veneer joints and 100 lb/Mft^2 of single glueline at the veneer-to-particleboard joints.

We tested structural load on a 90-inch test span rather than a 72-inch span because the test methods required by FHA engineers had not been finalized at the time of our tests. Fundamental formulas in structural engineering were used to

convert the bending moment and deflection for one type of span and test loading to those for another type. The converted values are reported in the following section.

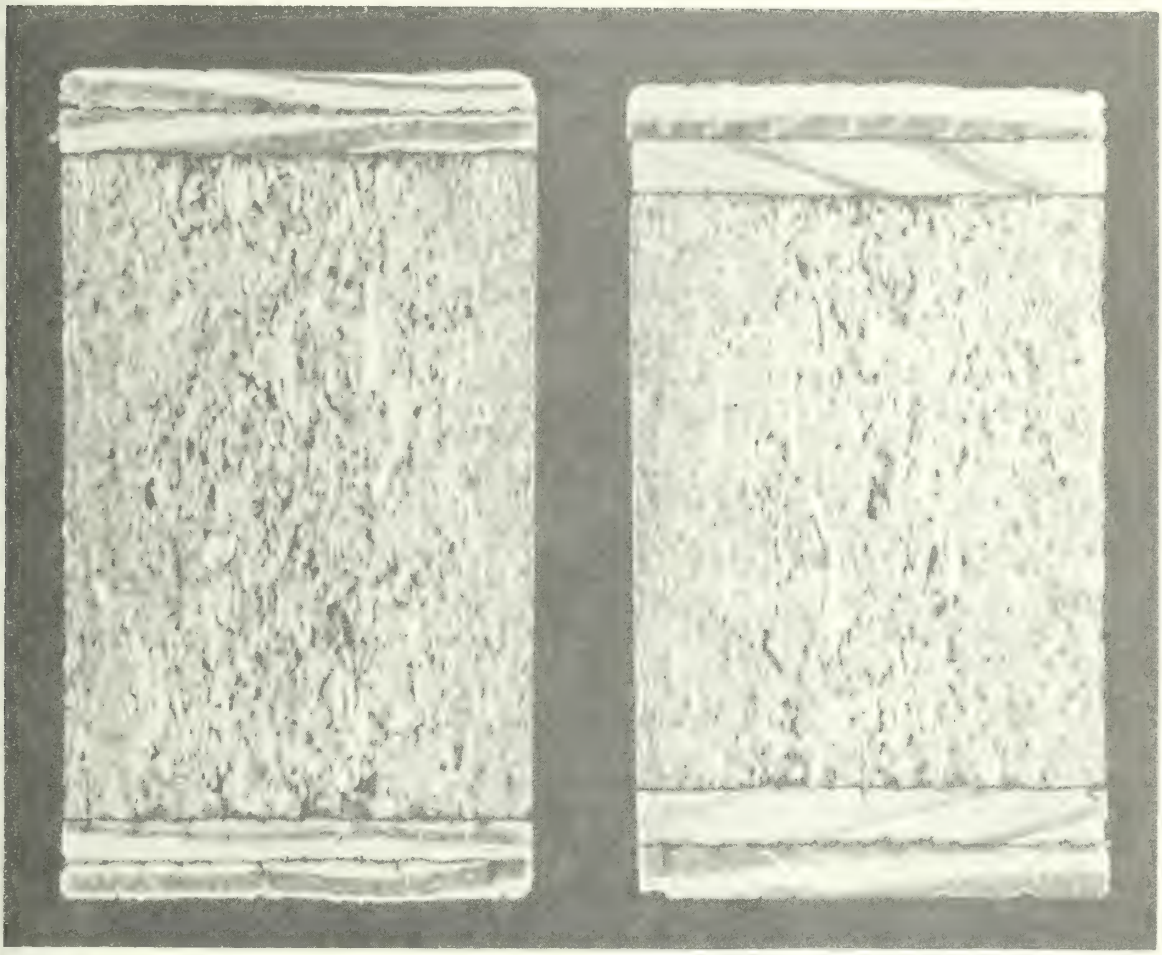

Figure 5.--End view of the two types of 2 x 3 COM-PLY studs. Stud with 1/8-inch-thick veneers is shown on the left; stud with 1/6-inch-thick veneers shown on the right.

ESULTS AND DISCUSSION

Average ultimate load of the 10 specimens with 1/8-inch-thick veneers was 84 pounds, and the standard deviation was 106 pounds. Average ultimate load of he 10 specimens with 1/6-inch-thick veneers was 834 pounds, and the standard eviation was 79 pounds. The formula for adjusting strength was used to convert he average ultimate loads of these samples to safe loads. Safe load was 278 ounds for the studs with 1/8-inch-thick veneers and 419 pounds for those with /6-inch-thick veneers. Safe resisting moment was 2,502 in-lb for the studs with /8-inch-thick veneers and 3,771 in-lb for those with 1/6-inch-thick veneers. oth groups of studs had strengths far greater than the required value of 1,130 n-lb.

When the 10 studs with 1/8-inch-thick veneers were loaded with two 60-pound oncentrated loads, the average deflection was 0.310 inch and the standard devia- ion was 0.028 inch. For the 10 studs with 1/6-inch-thick veneers, the corresponding alues were 0.268 inch for deflection and 0.026 inch for the standard deviation. hen the average deflections were adjusted, the value for the studs with 1/8-inch- hick veneers was 0.326 inch and that for the studs with 1/6-inch-thick veneers was

0.284 inch. Both groups of studs had adjusted deflections smaller than the maximum standard of 0.33 inch, although adjusted deflection of the studs with 1/8-inch-thick veneers approached this value.

These results indicate that COM-PLY partition studs made with southern pine should be fabricated with medium-density particleboard and that the veneers should be at least 1/8 inch thick. Stiffness, rather than strength, is apparently the limiting factor with 2 x 3 COM-PLY partition studs.

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COM-PLY partition studs made with two plies of 1/8-inch-thick southern pine veneer on each 1-1/2-inch face of a particleboard core of medium density are strong and stiff enough for use in interior nonload-bearing partitions in houses. These 2- x 4-inch partition studs can be used as a direct substitute for conventional 2- x 4-inch lumber studs and at the same spacings. Stiffness rather than strength controlled the design of COM-PLY partition studs.

KEYWORDS: Composite lumber, wood veneer, particleboard, southern pine, sandwich construction, structural research.

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Forest Service Research Paper SE-182 June 1978

Inhibitory Effects of Broomsedge Extracts on the Growth of Young Loblolly Pine Seedlings

by
David S. Priester
and
M. T. Pennington

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Southeastern Forest Experiment Station
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Inhibitory Effects of Broomsedge Extracts on the Growth of Young Loblolly Pine Seedlings

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Abstract.--Water extracts of live, dead, and decaying shoots of broomsedge (Andropogon virginicus L.) were applied to 4-week-old loblolly pine (Pinus taeda L.) seedlings for 7 weeks. Stem length of the pine was significantly reduced by extracts of both live and decaying broomsedge shoots. Root and needle lengths were significantly reduced by application of all broomsedge extracts; crown length was significantly reduced by live shoot extract. There were also significant reductions in ovendry weights for both stem and root portions of the pine. The extract treatments tended to increase nitrogen in the roots and to reduce nitrogen in the stems. Potassium and phosphorus were not affected by extract treatment. Paper chromatography of the extracts revealed 13 phenolic compounds, all of which were inhibitory to root elongation in a radish seed bioassay. Three of these compounds, tentatively identified as vanillic, m-coumaric, and m-hydroxyphenylpropionic acids, were found to be significantly more inhibitory than the others.

Keywords: Allelopathy, phenolic acids, Andropogon virginicus L., Pinus taeda L.

This investigation was prompted by a recent publication on the allelopathic effects of broomsedge (Andropogon virginicus L.) and its persistence in old fields in Oklahoma (Rice 1972). A successional species associated with old, abandoned fields (Quarterman and Keever 1962), broomsedge is widely distributed throughout the Southeast (Radford and others 1968, p. 163-165). Also associated with broomsedge in such fields is loblolly pine (Pinus taeda L.). In forest succession of old fields, broomsedge becomes dominant in about the third year after invasion, with loblolly pine dominating within 10 years (Wahlenberg 1960, p. 28-32).

The allelopathic qualities of broomsedge were first reported in Oklahoma by Rice (1972). He showed that root and shoot portions of both dead and live broomsedge were inhibitory to the growth of Amaranthus palmeri S. Wats.,

Bromus japonicus Thunb., Aristida oligantha Michx., and Andropogon scoparius Michx.; furthermore, that study determined that the causative agents were phenolic acids. Later, Rice (1974) found that broomsedge also inhibits growth of Rhizobium sp., Azotobacter sp., Amaranthus retroflexus L., Lespedeza stipulacea Maxim., and Trifolium repens L.

With the allelopathic effects of broomsedge and its association with loblolly pine having been established, the objective of our study was to determine the effect of broomsedge on the growth of loblolly pine seedlings.

MATERIALS AND METHODS

Water extracts of broomsedge were made up from the following sample types: (1) the dead shoot portion above ground--the materials were collected during the dormant season and stored in a dry, cool place for use as needed; (2) the live shoot portion above ground--shoots were collected as required throughout the growing season; and (3) the dead, decaying shoot portion of the previous year's growth--these materials were collected at the same time the live shoots were collected.

Extracts were prepared by soaking overnight an amount of cut-up plant material equivalent to 200 g (ovendry weight) in 100 ml of tapwater. This extract was then filtered through No. 1 filter paper and collected in bottles for treatment of greenhouse pots.

Twenty 2-liter pots filled with washed sand were placed on benches in the greenhouse and planted with 20 loblolly pine seeds per pot. Resulting seedlings were thinned to five per pot. A completely randomized design with five replications was used to test the effects of four different extracts on seedling growth and development. Each pot in a replication received one of the following treatments: (1) tapwater, (2) water extract of dead shoot portion, (3) water extract of live shoot portion, and (4) water extract of decaying shoot portion.

Treatments were applied daily by pumping extract from reservoirs beneath the benches up through holes in the bottoms of the pots, saturating the sand from below. After 15 minutes, the extracts were allowed to drain back into the reservoirs. Nutrients were supplied by weekly dosages of Hoagland's solution, which was applied from above (250 ml per pot). Care was taken to disconnect the extract apparatus so that any excess nutrient solution would not drain into the extract reservoirs.

Measurements of seedling height and needle length were made prior to treatment and every 2 weeks thereafter for the duration of the 7-week study. Initial measurements of heights and needle lengths showed no significant difference among treatments. Average seedling height was 47 mm, and average needle length was 26 mm. Final measurements included stem, root, needle, and crown lengths, as well as ovendry weights of the stems and roots. All seedlings from a pot were composited, with the stem and needle portions separated from the root. Ovendry tissues were ground and analyzed for total nitrogen according to the standard macro-Kjeldahl method (Black 1965, p. 1162-1168). Ash solutions were used to determine phosphorus by the vanadate-molybdate-yellow method (Black 1965, p. 1035-1049) and potassium by atomic absorption spectrophotometry.

As the study in the greenhouse progressed, we prepared, at 45° C under vacuum, six identical concentrations of each of the three broomsedge extracts. Each extract was concentrated from 500 ml to 5 ml of solution and then subjected to ether extraction of phenolic acids (DeBell 1971). In accordance with the methods of Smith (1960), 1 ml of each unknown phenolic acid solution was spotted on No. 1 chromatography paper for separation of phenolic compounds by the two-dimensional method with systems of iso-propanol-ammonia (20:1:2 mixture by volume of iso-propanol, ammonium hydroxide, and water) and benzene-acetic acid (125:72:3 mixture by volume of benzene, acetic acid, and water). After the positions of the separated phenolics were determined by ultraviolet light, they were tentatively identified as 13 different compounds by comparing Rf values with those found in the literature (Smith 1960). The resulting areas were then cut from the chromatogram and bioassayed with radish seed (DeBell 1971); the carrier was 3 ml of water.

RESULTS AND DISCUSSION

The growth pattern of the seedling shoots (fig. 1) indicates that growth differences began to develop 3 weeks after treatment. For all treatments, shoot growth more than doubled between the fifth and seventh weeks. During this same period, there was also a significant increase in the average needle length of the control seedlings over those receiving a broomsedge extract treatment.

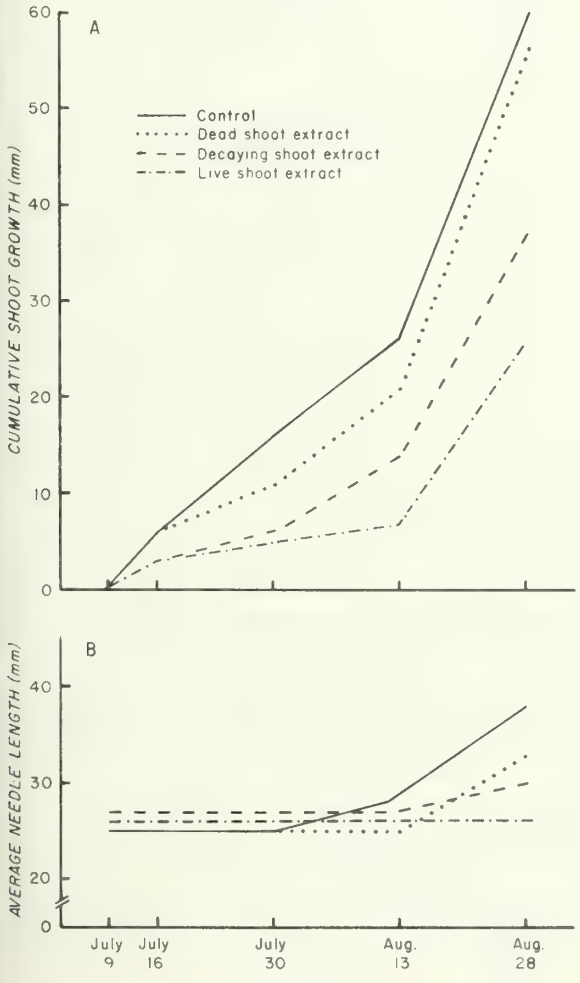

Figure 1.--Effects of extract treatments on (A) cumulative shoot growth and (B) average needle length of loblolly pine seedlings.

Root and needle lengths of loblolly pine seedlings were significantly reduced by extracts prepared from the dead, decaying, and live shoot portions of broomsedge (table 1). Stem length was reduced by the decaying and live shoot extract; crown length was reduced only by the live shoot extract. There were also significant reductions in the ovendry weights of the root and stem-needle tissue, along with significant increases in shoot/root ratio with the application of the live shoot extract (table 1).

Table 1.--Effects of extract treatments of broomsedge on size and weight of loblolly pine seedlings and on nitrogen, phosphorus, and potassium content after 7 weeks

Variable[1]	Tapwater control	Extract treatments of broomsedge		
		Dead shoot	Decaying shoot	Live shoot
		Millimeters		
Stem length	108_{a}	98_{ab}	89_{b}	71_{c}
Root length	261_{a}	187_{b}	204_{b}	111_{c}
Crown length	69_{a}	63_{a}	54_{ab}	37_{b}
Needle length	38_{a}	33_{b}	30_{bc}	26_{c}
		Grams		
Ovendry weight of stems and needles	1.6090_{a}	1.3104_{b}	1.2217_{bc}	0.9514_{c}
Ovendry weight of roots	1.1863_{a}	0.8410_{b}	0.6719_{bc}	0.4355_{c}
Shoot/root ratio	1.4370_{a}	1.5676_{a}	1.8197_{ab}	2.2297_{b}
		Percent		
Nitrogen in stems and needles	2.20_{a}	1.80_{b}	1.53_{c}	1.36_{c}
Nitrogen in roots	1.25_{a}	1.28_{a}	1.60_{a}	1.54_{a}
Phosphorus in stems and needles	$.11_{a}$	$.11_{a}$	$.11_{a}$	$.11_{a}$
Phosphorus in roots	$.11_{a}$	$.11_{a}$	$.11_{a}$	$.11_{a}$
Potassium in stems and needles	$.50_{ab}$	$.53_{a}$	$.40_{b}$	$.54_{a}$
Potassium in roots	$.59_{ab}$	$.72_{a}$	$.61_{ab}$	$.49_{b}$

[1] Treatment values for each variable with the same letter subscript are not significantly different at the 5 percent level according to Tukey's test.

Chromatography of the extracted phenolic acids indicated the presence of at least 13 phenolic compounds (table 2). Of the 13 compounds, the extract of dead broomsedge contained only 4 of these acids, a fact which may account for its being the least inhibitory of the 3 extracts (table 3). The extract made from decaying broomsedge contained 12 of the phenolic acids; that made from live broomsedge contained 11. Three of the phenolic compounds found in the extracts of decaying and live broomsedge (tentatively identified as vanillic acid, m-coumaric acid, and m-hydroxyphenylpropionic acid) were more inhibitory to

elongation of radish seed roots at the concentration used than were the other compounds (table 2). This increased inhibitory effect may have been due to their being in greater amounts or having higher potency than the other extracted phenolic compounds. We cannot identify these three specific phenolic compounds as being the most inhibitory to the growth of loblolly pine seedlings since the specific reagent chemicals were not applied to the seedlings. But since the extracts of broomsedge containing these phenolic acids inhibited growth of loblolly pine and since the radish seed bioassay showed them to be inhibitory, we surmise that these compounds were probably among the causative agents present in the extracts.

Table 2.--Tentative identification of phenolic acids in water extracts of broomsedge and average root elongation for radish seed bioassay for each compound when isopropanol-ammonia (IPrAm) and benzene-acetic acid (BzA) were used as solvents in a two-dimensional chromatography system

Rf values[1]				Tentative name of unknown phenolic acid	Radish seed root elongation[2]
IPrAm		BzA			
Unknown	Literature	Unknown	Literature		
					mm
00	00	20	22	Protocatechnic acid	31
03	03	24	25	Caffeic acid	35
04	06	76	83	Syringic acid	30
04	05	64	58	Iso-phthalic acid	27
06	07	81	85	Vanillic acid	22
00	00	75	65	Cinnamoylglycine acid	31
13	15	65	62	p-Coumaric acid	32
25	25	64	63	m-Coumaric acid	23
21	23	51	52	Pyrocatechnic acid	33
36	37	62	67	m-Hydroxyphenylpropionic acid	22
40	39	35	38	Gentisic acid	28
33	32	69	63	Phloretic acid	39
58	55	81	77	O-Hydroxyphenylpropionic acid	33
--	--	--	--	Distilled water control	88

[1] Literature values are from Smith (1960); all Rf values for unknowns are the average of at least 10 similarly positioned spots.

[2] Each value is the average of 100 seeds.

These results (table 3) show that a large number of these compounds were water soluble in the decaying and live broomsedge and occurred more frequently than they did in the extract of the dead material. It can be assumed from these data that the phenolic acid concentration in the decaying and live broomsedge was greater and therefore more inhibitory than the extract of the dead material.

Table 3.--Frequency of occurrence of the phenolic acids identified as present in the three broomsedge extracts

Phenolic acid	Extracts of broomsedge[1]		
	Dead material	Decaying material	Live material
	- - - - - Frequency - - - - -		
Protocatechnic	3	2	0
Caffeic	3	1	3
Syringic	1	0	1
Iso-phthalic	4	5	4
Vanillic	0	1	3
Cinnamoylglycine	0	1	1
p-Coumaric	0	1	3
m-Coumaric	0	1	6
Pyrocatechnic	0	2	3
m-Hydroxyphenylpropionic	0	1	3
Gentisic	0	1	3
Phloretic	0	1	0
O-Hydroxyphenylpropionic	0	1	4

[1] Six samples each of the three different extracts were analyzed.

In this study, the growth of both roots and shoots was reduced by the extract treatment, but root growth was more inhibited than shoot growth. Analysis of the roots and stems showed that toxicity did not affect the phosphorus and potassium levels (table 1). However, nitrogen in the stems was significantly reduced as toxicity of the treatment increased. Nitrogen in the roots showed a slight increase with increase of toxicity, but the correlation between nitrogen and increased toxicity was significant only at the 10 percent level. It is evident that the seedlings' metabolism of nitrogen was upset by the toxic leachate, which, when coupled with reduced root growth, probably caused the reduction in stem nitrogen and subsequent growth.

The significance of this report is that a biochemical interaction--allelopathy--between broomsedge and loblolly pine seedlings has been demonstrated in a greenhouse study. Further research is needed to determine whether allelopathy is an important factor in growth of loblolly pine seedlings under field conditions.

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Priester, David S., and M. T. Pennington

1978. Inhibitory effects of broomsedge extracts on the growth of young loblolly pine seedlings. U.S. Dep. Agric. For. Serv., Res. Pap. SE-182, 7 p. Southeast. For. Exp. Stn., Asheville, N.C.

Water extracts of live, dead, and decaying shoots of broomsedge (Andropogon virginicus L.) were applied to 4 week-old loblolly pine (Pinus taeda L.) seedlings for 7 weeks. Stem length of the pine was significantly reduced by extracts of both live and decaying broomsedge shoots. Root and needle lengths were significantly reduced by application of all broomsedge extracts; crown length was significantly reduced by live shoot extract. There were also significant reductions in ovendry weights for both stem and root portions of the pine.

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U.S. Department of Agriculture
Forest Service Research Paper SE-183

Evaluation of a Choctawhatchee Sand Pine Plantation at Age 35

by Russell M. Burns

U.S. Department of Agriculture - Forest Service

June 1978

Southeastern Forest Experiment Station
Asheville, North Carolina

Evaluation of a Choctawhatchee Sand Pine Plantation at Age 35

by

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Timber Management Research
Washington, D. C.[1]

Abstract.—Detailed measurements have been made of the only 35-year-old Choctawhatchee sand pine plantation known to exist. At age 35, 354 trees per acre had produced 3,150 cubic feet of pulpwood per acre to a 4-inch top. Average tree height was 56 feet and tree d.b.h. ranged from 5 to 15 inches, averaging 8.5 inches. Tree specific gravity averaged 0.49 and the wood contained 12.5 percent ethanol- and benzene-soluble extractives. The ovendry weight of organic matter accumulated in the A_{oo} through A_1 soil layers averaged 65.9 tons per acre. When measured at age 28, the plantation had reproduced a well-stocked stand of sand pine seedlings and saplings in the surrounding scrub hardwoods for a distance of 75 feet to the west (windward) and 130 feet to the east (leeward) of the plantation.

Keywords: Growth and yield, pulpwood volume, specific gravity, organic matter, reproduction.

Research suggests that 35 may be the economic rotation age for Choctawhatchee sand pine (Pinus clausa var. immuginata Ward) plantations grown for pulpwood in the sandhills (Burns 1973). The sand pine plantation on Eglin Air Force Reservation in Okaloosa County, Florida, was inventoried at that age. Because of the increasing demand for information about Choctawhatchee sand pine plantation growth and yield, detailed results of that cruise are presented here. Specific gravity and extractives, which may influence merchantability, are also discussed.

A report on this plantation at age 28 (Burns and Brendemuehl 1969) included history and descriptions of the soil and site; only the highlights are repeated here.

BACKGROUND

The $1\frac{1}{3}$-acre plantation forms a long, narrow rectangle oriented in a north-south direction. Bare-rooted wilding stock was established by bar planting at a 6- by 8-foot spacing amid native scrub oaks and wiregrass (mostly Quercus laevis Walt., Q. incana Bartr., and Aristida stricta Michx.) on a rolling upland sandhill site. The soil is Lakeland sand (a siliceous, thermic,

[1]When this research was conducted, Burns was Principal Silviculturist, Southeastern Forest Experiment Station, Marianna, Florida.

coated, typic quartzipsamment) with a pH range of 4.4 to 5.2. It is very low total nitrogen and in extractable phosphorus, potassium, calcium, and magnesium.

A ground fire burned the northern portion of the plantation sometime between the ages of 28 and 35 years. It caused no apparent damage to the planted trees in that portion of the stand, but undoubtedly killed many seedlings. Presented here are previously unpublished data concerning the reproductive potential of Choctawhatchee sand pine at plantation age 28. Data for the total plantation could not be obtained at plantation age 35 years because of the fire.

MEASUREMENTS

At plantation age 35, the following measurements were taken: total-tree height, d.b.h., merchantable height to an estimated 4-inch o.b. top, and double bark thickness at breast height. A single 4-mm increment core was taken at breast height from 257 trees to determine specific gravity. Litter was collected and newly established reproduction was counted on $\frac{1}{4}$-milacre plots at nine locations within the stand to estimate tons of litter produced per acre, the potential for soil organic matter incorporation, and stand regeneration.

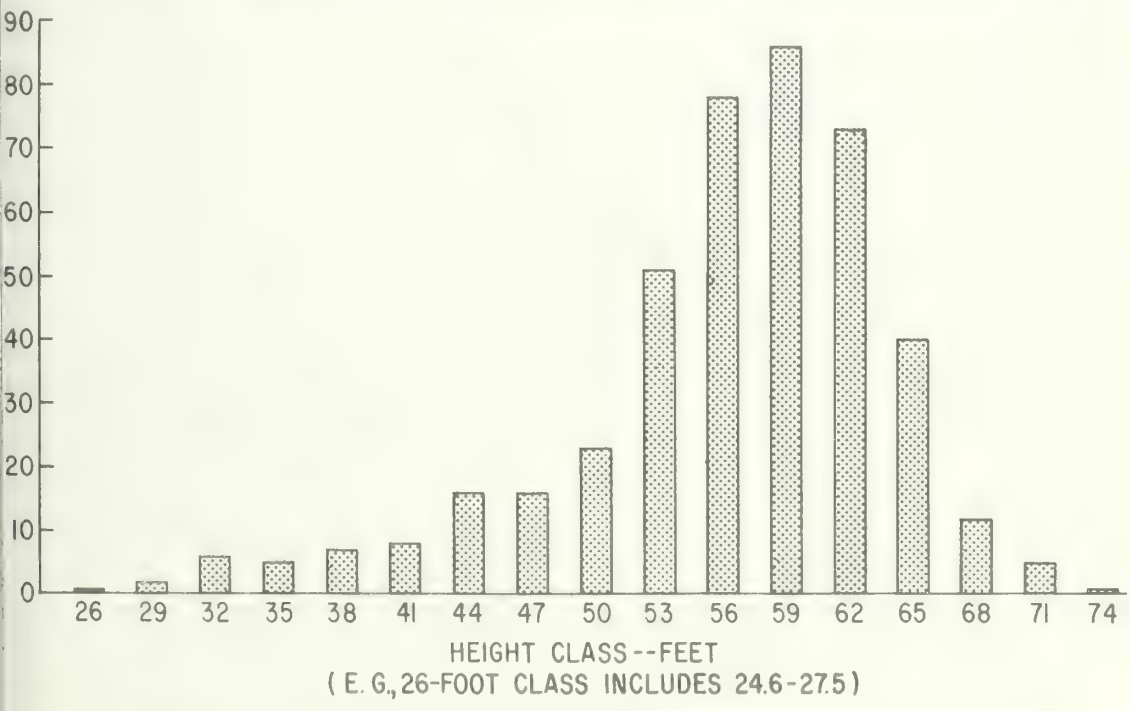
At age 28, the range of seed dispersal was estimated for this plantation. Sand pine seedlings 1 foot tall and taller were counted within 22 transects, each consisting of 50 adjacent 1-milacre square plots extending outward from the plantation edge.

TREE SIZE AND VOLUME

The sand pines have overtopped competing scrub hardwoods. Pines in rows bordering hardwoods developed atypically, tending toward large diameter, thick bark, and many limbs. Trees growing in the interior rows (1.159 acres total) of the plantation exhibited more typical development (fig. 1). Therefore, reference will be made only to trees in the interior of the 35-year-old stand unless noted otherwise.

At age 35, tree heights ranged from 12 to 75 feet; the majority of trees were between 53 and 65 feet tall (fig. 2). Most trees less than 6 inches, shown in figure 3, resulted from natural regeneration. All living planted trees have attained a harvestable size, the majority within the 7- to 10-inch d.b.h. class.

Figure 1.—Interior of the Choctawhatchee sand pine plantation at age 35.



gure 2.—Height frequency distribution of 430 trees (4 trees less than 24.6 feet tall not shown) exclusive of border rows at plantation age 35.

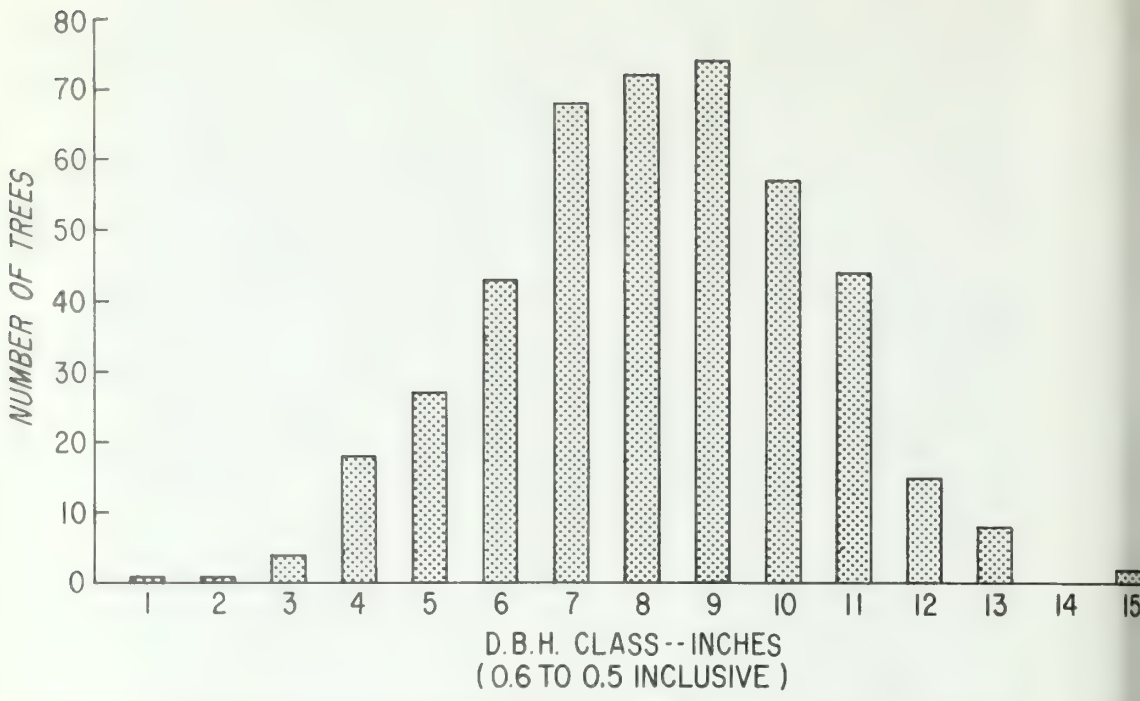


Figure 3.—Diameter frequency distribution of 434 trees (exclusive of border rows) at plantation age 35.

Generally, trees with large d.b.h. tend to be taller, to contain more merchantable length, and to have thicker bark than those of small d.b.h. (table 1). It is not surprising, therefore, that total-tree height, estimated merchantable height, and double bark thickness at breast height are closely correlated with d.b.h. Regression analysis was used to develop equations representing these relationships (fig. 4). All correlations are significant at the 1 percent level of probability.

A local stand-volume table was developed from trees 5 inches d.b.h. and larger (table 2). To estimate pulpwood yield in cubic feet, tree bole volume

Table 1.—Measurements on trees 5 inches d.b.h. and larger in the interior 1.159 acres of the plantation

Measurement and unit of measure	Average	Range	
		Minimum	Maximum
Total height (feet)	56.1	34	76
D.b.h. (inches)	8.53	5	15
Merchantable height (feet)	37.3	6	55
Double bark at breast height (inches)	.65	.18	2.00

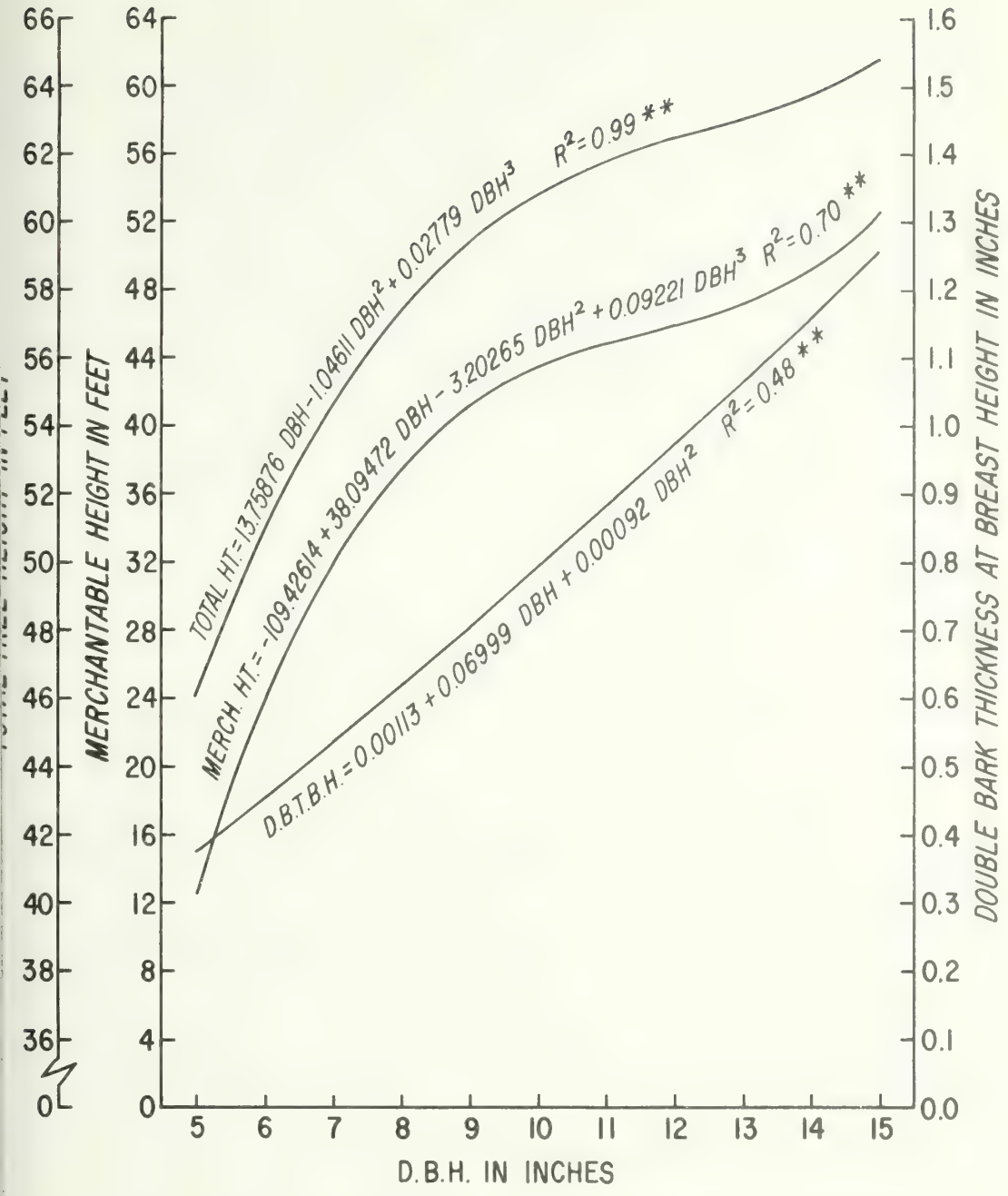

TOTAL HT.=13.75876 DBH-1.04611 DBH² + 0.02779 DBH³ R²=0.99**
MERCH HT.=-109.42614+38.09472 DBH-3.20265 DBH² + 0.09221 DBH³ R²=0.70**
D.B.T.B.H.=0.00113+0.06999 DBH+0.00092 DBH² R²=0.48**
MERCHANTABLE HEIGHT IN FEET
DOUBLE BARK THICKNESS AT BREAST HEIGHT IN INCHES
D.B.H. IN INCHES

Figure 4.—Regression equations of tree height, merchantable height, and double bark thickness of plantation-grown Choctawhatchee sand pine at age 35.

re computed to an estimated 4-inch d.o.b. top using the equation for mer-antable height (MH), the average d.b.h. for each diameter class, and the ne-frustrum formula:

$$\text{Volume} = 0.2618\ (\text{MH} - 0.5)\ \frac{D^2 + Dd + d^2}{144}$$

ere

D = d.b.h. and d = top diameter = 4 inches.

Table 2.—Stand-volume table for merchantable trees in the interior 1.159 acres of the plantation[1]

D. b. h. (inches)		Trees	Height		Volume	
Class	Average		Total	Merchantable	Merchantable[2]	Total[3]
		No.	- - - Feet - - -		- - - Cubic feet - - -	
5	5.1	27	46.6	13.8	40.74	68.04
6	6.1	43	51.3	24.7	146.82	183.13
7	7.0	68	54.6	31.9	361.01	411.67
8	8.1	72	57.6	38.0	559.63	608.16
9	9.0	74	59.4	41.2	728.24	776.38
10	10.0	57	60.8	43.5	695.12	731.91
11	11.1	44	61.8	44.9	652.12	681.11
12	12.1	15	62.6	46.0	261.57	271.70
13	12.9	8	63.1	47.0	158.26	163.71
14	14.0	0	63.8	49.2	0	0
15	15.1	2	64.9	53.0	58.11	59.36
Total		410	--	--	3,661.62	3,955.17
Total per acre		354	--	--	3,159.29	3,412.57

[1] Values for total tree height and merchantable height to an estimated 4-inch o. b. top are from the regressions depicted in figure 4.

[2] Merchantable volume in cubic feet = 0.2618 (merchantable height - 0.5) $\frac{D^2 + d^2 + Dd}{144}$, where D = d. b. h. and d = 4 inches d. o. b.

[3] Total bole volume = 0.001818 (merchantable height) $(D^2 + 16 + 4D)$ + 0.029088 (total height - merchantable height).

To estimate topwood yield in cubic feet, the volume of wood remaining above the 4-inch merchantable top was computed using the conical formula:

$$\text{Volume} = 0.001818\ d^2\ \text{height}$$

where

d = 4 inches, height = total minus merchantable height, and total height (TH) is from the regression equation.

Topwood volume was added to the volume computed by the cone-frustrum formula to obtain total volume of the tree bole. The combined formula for determining volume was simplified to read:

$$\text{Volume} = 0.001818\ MH\ (D + 16 + 4D) + 0.029088\ (TH - MH).$$

Numbers of trees, heights, and volumes are shown by diameter class in table 2. If we accept Mesavage's[2] estimate of 74.1 cubic feet per rough cord, the plantation contained 42.6 rough cords per acre of merchantable volume and 46.0 cords of total volume at age 35. The yield per acre per year was 1.22 cords of merchantable wood.

Under intensive utilization, the stump and a major portion of the central root core (taproot) also may be harvested. No data are available on the percentage increase in yield expected from harvesting taproots of sand pine. However, according to industry foresters, the green weight of tree-length slash pines harvested in northwest Florida increased approximately 8 to 10 percent when taproots were taken. Until data for sand pine are obtained, a similar percentage increase might be anticipated and added to total-tree volumes in table 2 to approximate bole volumes, including stumps and taproots.

SPECIFIC GRAVITY

Increment cores 4 mm in diameter were taken from 257 trees in the interior stand, and their specific gravities were computed by the maximum moisture method (Smith 1954). Tree specific gravity was determined before and after benzene- and ethanol-soluble components were extracted by the method of Clark and Taras (1969). The total-tree specific gravity was then estimated from core specific gravity using an equation developed by the same authors for Choctawhatchee sand pine. Results are summarized by average diameter in each 1-inch d.b.h. class in table 3.

The specific gravity of sampled trees averaged 0.49, just over the 0.48 average published for Choctawhatchee sand pines in southwest Alabama and northwest Florida (Clark and Taras 1969). The specific gravity of only four pines equals or exceeds that of Choctawhatchee sand pine: South Florida slash pine (P. elliottii var. densa, Little and Dorman) (0.58), slash pine (P. elliottii Engelm.) (0.53), longleaf pine (P. palustris Mill.) (0.53), and table-mountain pine (P. pungens Lamb.) (0.49). The specific gravity of the remaining southern pines growing on native sites is lower than that of Choctawhatchee sand pine: loblolly pine (P. taeda L.) (0.47), shortleaf pine (P. echinata Mill.) (0.47), pond pine (P. serotina Michx.) (0.47), pitch pine (P. rigida Mill.) (0.47), Virginia pine (P. virginiana Mill.) (0.45), spruce pine (P. glabra Walt.) (0.43), and Ocala sand pine (P. clausa var. clausa Ward) (0.42) (Taras 1973). The commercial importance of differences in specific gravity is apparent when considered on a weight-equivalent basis. For trees of similar form and dimension, a difference of 0.01 specific gravity unit amounts to approximately 50 pounds of wood per standard cord (Saucier 1972).

EXTRACTIVES

The amount and composition of extractives are important in determining the potential value of a pine to the pulp and chemical industries. On the average, Choctawhatchee sand pine yields a higher percentage of extractives (9.7)

[2]Mesavage, Clement. 1947. Tables for estimating cubic-foot volume of timber. USDA For. Serv., South. For. Exp. Stn. Occas. Pap. 111, 71 p.

than any of the other southern yellow pines except the South Florida variety o slash pine (12.4) (Saucier 1972). The chemical composition of Choctawhatche sand pine wood includes slightly less lignin (an undesirable component), mor holocellulose (usable cellulose component), and more pentosan (used in th manufacture of furfural for phenolic resins) than longleaf, slash, or Ocala san pine (Taras 1973). In addition, the sand pines are the only southern pines tha contain relatively large amounts (10 percent) of camphene (used in medicin

Table 3.—Core and tree specific gravity of 257 Choctawhatchee sand pines showing th percentage of benzene-ethanol extractives

Average d.b.h.[1]	Trees	Specific gravity[2]			Extractive content[4]
		Unextracted core	Extracted core	Unextracted tree[3]	
Inches	No.				Percent
3.0	1	0.4389	0.4237	0.4784	3.59
4.3	7	.4989	.4481	.4956	11.34
5.1	16	.5047	.4398	.4878	14.76
6.1	22	.5083	.4491	.4935	13.18
7.0	41	.5056	.4507	.4934	12.18
8.1	53	.5113	.4518	.4925	13.17
9.0	49	.5155	.4603	.4978	11.99
10.0	35	.5114	.4528	.4903	12.94
11.0	23	.5306	.4693	.5017	13.06
12.0	8	.4787	.4343	.4725	10.22
12.8	2	.4767	.4408	.4763	8.14
Total	257	--	--	--	--
Average (all trees)		.5104	.4531	.4933	12.63
Average (6 inches) d.b.h. & larger		.5114	.4543	.4936	12.56

[1] Trees smaller than 6 inches d.b.h. are considered reproduction and less than 35 years old.

[2] Specific gravity = $\frac{\text{Ovendry weight}}{\text{saturated weight - 0.3464 ovendry weight}}$.

[3] Tree specific gravity = 0.14879 + 0.78915 (specific gravity of extracted core) 0.05552 (d.b.h./age), where age = 35.

[4] Percent extractives (percent difference between unextracted and extracted cor $\frac{\text{Unextracted specific gravity - extracted specific gravity}}{\text{extracted specific gravity}} \times 100$.

and in the manufacture of synthetic camphor) in their gum turpentine (Mirov 1961).

Tall oil, a byproduct of the black liquor from the sulfate or kraft paper process, is valuable because it contains recoverable amounts of long-chain alcohols and sterols. Yields of tall oil, and of the benzene-ethanol extractives with which tall oil is correlated, can be genetically manipulated (Franklin, Taras, and Volkman 1970). For this reason, the comparatively high percentage yields of extractives from unimproved Choctawhatchee sand pine should interest chemists and geneticists in research aimed at increasing yields through genetic selection, manipulation, and improvement.

Extractives averaged 12.63 percent for the 257 trees sampled. However, approximately one-fifth (51/257) of the increment cores were from trees in the northern one-sixth of the stand—the portion that burned. Extractives from trees in the burned area averaged 13.18 percent, compared to 12.49 percent for those in the unburned portion. The higher proportion of extractives from trees in the burned area may have resulted from injury by fire, differences in site or exposure, or a combination of these and other factors. Even the extractive content of samples from the unburned portion of the plantation (12.49 percent) is higher than the 9.7 percent previously observed for Choctawhatchee sand pine in southwest Alabama and northwest Florida and as high a natural resin content as slash pines from south Florida.

ORGANIC MATTER

Organic matter is virtually the only source of cation exchange in sandhill soils. As such it serves as a reservoir of nutrients for plant growth. Therefore, factors that increase the organic fraction of sandhill soils also increase potential productivity. Surprisingly large amounts accumulated, particularly in the last 7 years.

The ovendry weight of $\frac{1}{4}$-milacre samples of the A_{oo} through A_1 horizons that were retained by the 2 mm mesh of a soil sieve averaged 52.2 tons per acre. The fire that burned the northern portion of the plantation did not consume the litter uniformly. One of three sample plots in the burned portion yielded only 9.6 tons; a second contained 46.7 tons, while the third had 18.2 tons for an average of 25.0 tons of organic matter per acre. The accumulation was somewhat more uniform in the unburned portion of the plantation, ranging from a low of 48.2 tons to a high of 80.8 tons and averaging 65.9 tons per acre. On an annual basis, this amounts to almost 1.9 tons per acre per year for 35 years.

Ovendry litter from all sample plots averaged 8.5 tons per acre at age 28 and 52.2 tons per acre at age 35. This amounts to an average annual accumulation of 6.2 tons per acre per year over the 7-year period. A similar comparison from only unburned portions of the stand shows an annual rate of increase of 8.2 tons per acre. Either figure attests to the important ameliorating effect of a Choctawhatchee sand pine plantation on impoverished sandhill soil and suggests that some of these effects may be lost if the plantations are harvested too early.

A cross section of a portion of the A-horizon (A_{oo} through A_1 layers) from the unburned stand where the sample yielded 80.8 tons per acre is illustrated in figure 5. It averaged almost 4 inches thick. Of this, the A_{oo} and A_o layers together accounted for $2\frac{1}{4}$ inches. The A_1 layer was more than $1\frac{1}{2}$ inches thick, and, with the A_o layer, contained many of the roots of recently germinated pine seeds and other newly established plants. Larger roots from pines of the overstory were not sampled, nor were they unduly disturbed. The entire phalanx of organic components, from canopy to litter, ameliorates the refractory sandhill environment and improves the prospective productivity of the soil.

REPRODUCTION

The plantation was the only source of Choctawhatchee sand pine seed in the area. This provided an opportunity to estimate the reproductive potential of sand pine in relation to the natural conversion of the surrounding scrub hardwoods to pine. The range and pattern of seed dispersal were estimated by evaluating the number of Choctawhatchee sand pine seedlings on 22 transects.

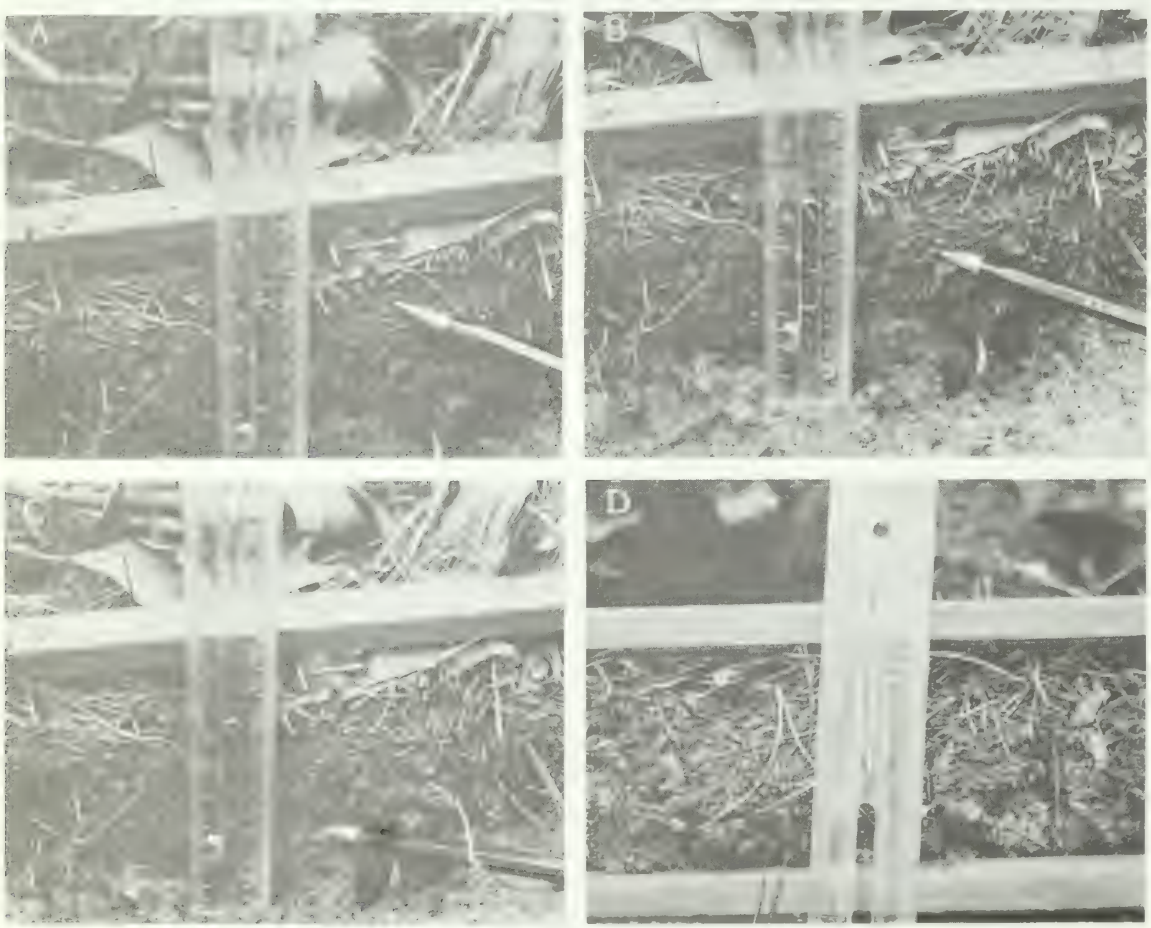


Figure 5.—Cross section of a portion of the A-horizon. (A) The A_{oo} (L or litter) layer is between the stick and the point of the pencil. (B) The A_{oo} and a portion of the A_o (L + F or fermentation) layers are above the pencil point. (C) The A_{oo} and A_o layers together account for about $2\frac{1}{4}$ inches of the 4-inch profile illustrated. The A_1 layer is about $1\frac{1}{3}$ inches thick and is below the pencil point. (D) The A_{oo} and A_o layers, located between the two sticks, formed a coherent mass and could be lifted easily without undue breakage.

The pattern of seedling establishment along the transects illustrates the importance of wind direction at the time of seed fall on the distribution of Choctawhatchee sand pine from a central source (fig. 6). Prevailing winds are from the west, i.e., southwest during summer and northwest during winter. In general, winds are from the northwest when sand pine seeds are disseminated during the months of September, October, and November.

At plantation age 28, seedlings were more evenly distributed over a greater distance on the leeward than on the windward side of the plantation. Along the western edge, sand pine seedlings were found for a distance of only 75 feet, or approximately 1.5 times average tree height (54 feet at age 28). East of the plantation, reproduction was well established in sufficient numbers for a well-stocked stand for a distance of 130 feet and a lightly stocked stand for an additional 50 feet. Isolated Choctawhatchee sand pine seedlings were observed beyond the bounds of the sample area in all but the northwest transect. A cursory examination of the unburned portion of the same area at age 35 showed that the area containing Choctawhatchee sand pine reproduction had enlarged and that the intensity of stocking had increased, particularly to the east and southeast of the plantation. Some of the reproduction had already overtopped the scrub hardwoods.

Occasionally, small catastrophes will open up small areas within a plantation. Yet within this plantation, natural reproduction has maintained a fully stocked condition, as illustrated in figure 2. Sand pine seedlings were sampled at age 28 on seven $\frac{1}{4}$-milacre plots spaced throughout the plantation and on nine such plots at age 35. At age 28, six of the seven plots (86 percent) contained one or more seedlings, and stocking of seedlings averaged 8,600 per acre. The southern section of the plantation contained more seedlings than any other section. The number of seedlings appeared correlated with tree height. At age 35, all nine of the sample plots contained more than one seedling, and stocking averaged 24,000 seedlings per acre. The burned northern portion contained more seedlings than the unburned southern portion of the plantation. Throughout the plantation, seedling numbers were higher where the organic overburden was lightest ($r = -0.80$ significant at the 1 percent level).

Based upon these observations and upon measurements of sand pines underplanted amid established scrub hardwoods, land managers can expect naturally and artificially established sand pines eventually to overtop their competitors in the sandhills. However, they can also expect significantly faster sand pine growth if release is provided soon after the pines are established. Furthermore, if fires that kill parent trees are excluded and cuttings timed to take advantage of seed fall, it should not be difficult to naturally regenerate sand pine.

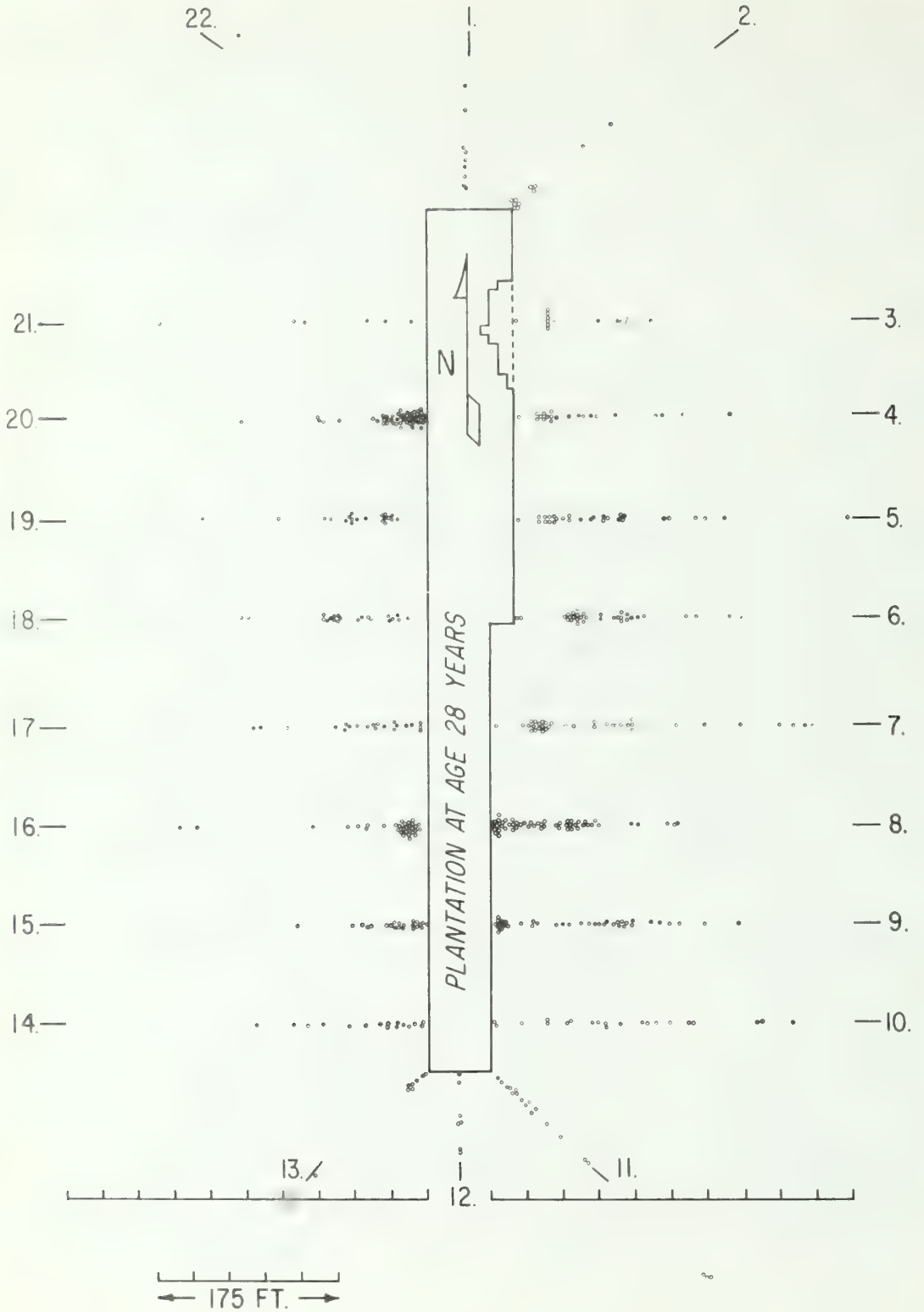


Figure 6.— Distribution of reproduction along twenty-two 330-foot transects from a 28-year-old Choctawhatchee sand pine plantation.

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Detailed measurements have been made of the only 35-year-old Choctawhatchee sand pine plantation known to exist. At age 35, 354 trees per acre had produced 3,150 cubic feet of pulpwood per acre to a 4-inch top. Average tree height was 56 feet, and tree d.b.h. ranged from 5 to 15 inches, averaging 8.5 inches. Tree specific gravity averaged 0.49 and the wood contained 12.5 percent ethanol- and benzene-soluble extractives. The ovendry weight of organic matter accumulated in the A_{00} through A_1 soil layers averaged 65.9 tons per acre. When measured at age 28, the plantation had reproduced a well-stocked stand of sand pine seedlings and saplings in the surrounding scrub hardwoods for a distance of 75 feet to the west (windward) and 130 feet to the east (leeward) of the plantation.

Keywords: Growth and yield, pulpwood volume, specific gravity, organic matter, reproduction.

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The Forest Service, U. S. Department of Agriculture, is dedicated to the principle of multiple use management of the Nation's forest resources for sustained yields of wood, water, forage, wildlife, and recreation. Through forestry research, cooperation with the States and private forest owners, and management of the National Forests and National Grasslands, it strives—as directed by Congress—to provide increasingly greater service to a growing Nation.

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Management of Forests for Timber and Related Benefits (DYNAST-TM)

by
Stephen G. Boyce

U.S. Department of Agriculture-Forest Service

February 1978

Southeastern Forest Experiment Station
Asheville, North Carolina

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Management of Forests for Timber and Related Benefits (DYNAST-TM)

by

Stephen G. Boyce, Chief Forest Ecologist
Asheville, North Carolina

Abstract.--A technique is described for harmonizing forest management actions to provide timber as the primary product but also to provide a desirable combination of related benefits. The system is cybernetic in that it is guided toward a goal by feedback processes.

Keywords: Multiple benefit, silviculture, forest management, system dynamics, cybernetics, timber, wildlife.

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1. INTRODUCTION

1.1 The Problem and a Solution

Industrial forest lands are managed to produce acceptable returns on investments and provide raw material for industry. Naturally, the emphasis has been on harvesting timber, and little has been done deliberately to enhance timber-related benefits, such as hiking, hunting, camping, and the enjoyment of wilderness, which may or may not be sources of revenue.

However, it is becoming evident that forest businesses would do well to pay more attention to these other benefits available from the forest (Seaton 1973; Clawson 1974; Stephens 1977). The dollar value of a year's growth in a stand of pulpwood or sawtimber is not great; it may easily be rivaled by the value of a year's recreational use. At present, forest businesses do not get much direct return from recreational use of land, but the

explosive growth in outdoor recreation suggests that such use will be of increasing value to landowners, in dollars as well as in public relations. A style of forest management which enhances recreational value could certainly affect the terms of revenue-yielding use agreements, public attitudes toward the forest industry, and the climate in which it does business.

What will it cost? That is the first question to arise because we are accustomed to think that these other benefits can be enhanced only at the expense of the basic objectives of forest businesses. This assumption is ingrained in the science of forestry. The classical systems of silviculture assume disharmony among the various objectives of forest management, and none of those systems originally included actions to enhance timber-related benefits. But these other benefits have value as real as the value of the pulpwood or sawtimber, and their production does not in every case conflict with the production of wood.

Current methods of analysis cannot yield a comprehensive estimate of the whole array of benefits produced under different sustainable patterns of timber harvest. Methods are now available to compromise the production of timber for a selected group of related benefits. In these systems, linear programing techniques are used to work through an array of goals from the highest to the lowest priority as established by the forest owner (Adams and Ek 1974; Leuschner and others 1975; Meadows and others 1975; Chappelle and others 1976). These techniques are useful when one can limit management objectives to one or a few related benefits, when the variety of benefits can be matched on a one-to-one basis with a variety of management actions, and when one benefit, usually timber, can be optimized (Wagner 1975). However, biologically possible combinations of benefits and harmony of management actions are not assured in perpetuity.

This report describes a management system for directing the biological systems of the forest to provide timber and related benefits in biologically possible combinations over long periods of time. The system is cybernetic in that it is guided toward a goal by feedback processes. It is based on a computer model of the managed forest in which the harvest of timber is regulated to guide the model forest toward a steady state yielding a constant annual flow of harvested timber and related benefits. The model is adapted from the studies of biology, forestry, cybernetics (Weiner 1948), management concepts (Beer 1966), and industrial dynamics (Forrester 1961, 1968). It uses notations for the DYNAMO compiler (Pugh 1976).

This system is a modification of that described in "Management of Eastern Hardwood Forests for Multiple Benefits, DYNAST-MB" (Boyce 1977). DYNAST-MB was designed for forest areas managed explicitly for multiple benefits. It allows the forest to be managed as two sectors with different rotation periods, thus providing a very wide range of habitats for wildlife and esthetic or recreational values. The system described here is a simpler one with a single rotation period. It is designed for areas where timber production has priority, but where managers wish to examine the possibilities for enhancing other benefits.

1.2 An Overview of the Presentation

The first two chapters of this report explain the nature and the function of the DYNAST-TM system for a general readership. The remainder of this introductory chapter will discuss the relation between the physical organization of the forest and the production of timber and related benefits, and will go on to show how a computer model can be used to predict and evaluate the consequences of various patterns of management. Chapter 2 describes the generalized structure of the DYNAST-TM model--how the model traces the changing physical organization of the forest and estimated timber and related benefits. Chapter 3 explains how the DYNAST-TM model would be applied in the management of a real forest.

Chapter 4 is directed toward readers who desire a technical explanation of the model as a basis for making modifications. Chapter 5 describes the supplementary equations, or algorithms, which extrapolate benefits from the physical organization of the modeled forest. These have been modified from the DYNAST-MB version only when necessary to fit the TM core model. In chapter 6, the printouts for six model runs are analyzed; these project the benefits resulting from six patterns of timber harvest for the same specific area of Appalachian forest as used to illustrate the DYNAST-MB model. These printouts may be compared directly between the two models. The appendixes list definitions, abbreviations, and equations used in the current version of the DYNAST-TM model. Equations are referred to parenthetically in the text, for example, (Eq. 3,R). These equations are defined in appendix A.

1.3 DYNAST-TM

A model is a representation of some aspect of reality. All decisions and actions are based on models, which may be mental (a plan for a day's activities), physical (a floor plan for a building), or mathematical. Simple descriptive models can be envisioned without extensive documentation. Whenever the models become too large to be envisioned in their totality at one time, computers are used to link large numbers of mathematical equations and to display the interrelationships as charts, diagrams, and tables. The computer and the mathematical equations are tools that organize and display parts of models in the same way a pencil is used to display a sentence on paper.

DYNAST is a system dynamics model that is different from descriptive models in several important ways. First, the theory of feedback systems is used to relate the information available from mental models and thus form a cybernetic structure. Second, four bionomic theories (Boyce 1977, chapter 4), which are mental models, are used to organize information to reflect changes in the forests being managed. Third, information that would otherwise stay in verbal, descriptive form is converted to an explicit display of interrelationships which can be used for making management decisions. This means that all the assumptions, which are derived from scientific research and experience, become quantitative and are displayed in interactive relationships approximately as they occur in the forest.

The purpose of DYNAST-TM is to guide the management of the forest toward the production of whatever possible combination of timber and related benefits its managers choose. The model's structure is designed to maintain a regular flow of timber and related benefits for acceptable returns on investments in commercial forest businesses. DYNAST allows the assessment

of an infinite number of alternatives for management by predicting how each policy would affect timber production, habitat for a number of animal species sediment flow, and the esthetics of the landscape. It can enhance human decision-making and help forestry management to balance returns in relation to investments. Once the alternatives have been assessed and a course of action chosen, the model serves a second function: it helps to guide the management of the forest toward the selected goal by indicating rates and patterns of timber harvest for each year. A third function is to use feedback processes to adjust actions to unexpected changes in markets and to changes in the forest that may result from wildfires, insects, and diseases.

1.4. A Preview of the Solution

1.4.1 The Relation of Benefits to Forest Habitats

Each kind of forest community provides a different combination of benefits for man. For example, a stand of old-growth timber offers den trees for bear and mast for squirrels, but little browse for deer; undisturbed, the old-growth stand minimizes sediment flow into streams but also minimizes the annual runoff of water. Once harvested, the large logs provide premium wood for furniture and paneling. Other types of community produce other benefits, and a mixture of types within a limited area would yield yet another combination of benefits.

The important point is that the benefits available from a given forest depend primarily on the proportion and physical distribution of what may be called habitats, differing forest communities dominated by particular age classes.

Before the advent of forest management, the distribution of habitats in a forest was shaped by wildfire, diseases, insects, the forces of weather, and human disturbances. These disturbances frequently created openings large enough to permit the growth of seedlings and sprouts which were followed, in time, by a succession of age classes. In a managed forest, the distribution of habitats is under human control. Regulated removal of trees makes openings which establish the future succession of communities. Because the distribution of habitats is, in the long run, controllable, and because forest benefits may be estimated for a given distribution of habitats, the way is clear for systematic management for timber and related benefits. The biological theory underlying this argument is explained in chapter 4 of the DYNAST-MB report (Boyce 1977).

Once supplied with coefficients for a particular locale, the DYNAST-TM model predicts the distribution of habitats that results from a given rotation period and the timber and related benefits which that distribution of habitats would yield. DYNAST guides the model forest toward a steady state in which the distribution of habitats remains constant; it also reveals how long the forest would take to reach a steady state and what benefits would be available in the interim.

Using these model runs, forest managers can explore the consequences of many different periods of rotation, here called "modes of management." First, managers can preview the biologically possible harvest of timber and related benefits available for the locale. Secondly, they can choose the mode of management which leads to the most acceptable returns on investments. Finally, they can apply the chosen mode of management by selling timber at the rate specified by the model for each year, choosing tracts of an age and area defined by the mode of management.

1.4.2 The Classification of Habitats

Since the system is based on the relationship between forest benefits and habitats, or types of forest community, a practical classification of habitats must be made for the area under study. The continuum of succession must be divided into classes that are significant for the benefits being considered. The classification will vary for different types of forest and can be modified whenever a new relationship is discovered between a particular age class and a particular benefit. The examples of modeling presented in this report use the following classification of the Appalachian hardwood forest:

Seedling habitats.--Stands with half of the dominant and codominant trees less than 1-inch d.b.h. (2.5 cm). A few scattered large trees are admitted.

Sapling habitats.--Stands with half of the dominant and codominant trees between 1 and 5 inches d.b.h. (2.5 to 12.4 cm). A few scattered large trees are admitted.

Pole habitats.--Stands with half of the dominant and codominant trees between 6 and 11 inches d.b.h. (12.5 to 27.7 cm). Pole habitats are classified by 2-inch (5 cm) diameter classes as pole-6, pole-8, and pole-10 habitats.

Mature timber habitats.--Stands with half of the dominant and codominant trees between 11 and 16 inches d.b.h. (27.8 to 40.6 cm).

Old-growth habitats.--Stands with half of the dominant and codominant trees larger than 16 inches d.b.h. (40.7 cm).

1.4.3 The Modes of Management

DYNAST-TM projects the distribution of these habitats resulting from different patterns of harvest, or modes of management. Two variables compose a mode of management: the length of the rotation period and the size of openings created when timber is removed.

The first variable is the rotation period, the age for harvest of timber. Managers often select the age when the mean annual increment is largest. However, for most kinds of forests the mean annual increment varies little over a wide range of ages (Forbes 1961, sec. 3). Thus with little loss of timber production, the rotation period may be adjusted to produce a desired size of timber, to reduce the period for investment, or to change the distribution of habitats and thus the availability of timber-related benefits. These changes can often lead to pure economic benefit rather than the conflict of objectives often assumed. For each mode of management the model is programed for a single period of rotation, but a very large number of rotation periods can be examined with multiple runs.

The size of openings is the second variable in the mode of management. Large openings lead to efficient harvest of timber because fewer roads and skid trails are needed in proportion to the volume of timber removed. However, small openings are probably desirable esthetically, and they may aid wildlife by concentrating a variety of habitats within a relatively small area. The model can be programed for a mean opening size and an acceptable range of deviation from the mean.

The modes are designed in this report by length of rotation period and size of opening. That is, the mode 40/40 has a rotation period of 40 years with openings of 40 acres. Size of the openings is varied by a normal deviate function. For example, if the 40-acre openings can be permitted to vary ± 4.8 acres, this variance is divided by 2.4 and the constant used in the program is 2.

The main function of DYNAST is to allow the efficient screening of these modes of management. The computer prints out tables, which give estimated yields of timber and related benefits, and graphic plots, which show how the yields fluctuate and then move toward a steady state. To illustrate the process, the program has been run in six modes for a particular real forest. The area used for the example is 6,396 acres of deciduous forest on National Forest lands in Buncombe County, North Carolina, for which a recent inventory provides data on the present distribution of habitats. The same example was used to illustrate the DYNAST-MB program (Boyce 1977), so the dynamics of the two models can be directly compared. Table 1 gives the control constants for the six modes of management. All six modes, with complete tables and plots, are analyzed in chapter 6. As an introduction to the screening process, table 2 shows some of the data for mode 40/40.

Table 1.--The control constants for six selected examples of modes of management[1/]

Controls	Rotation period (years) (ROT)					
	20	40	80	160	240	300
Size of opening (acres) (ISO)	50	40	25	10	5	1
Variance in opening size divided by 2.4 (acres) (ISD)	5	2	1	1	0.3	0.2

[1/]Detailed descriptions are in chapters 3, 6, and the appendix. Modes are designated by the rotation period and the size of openings, i.e., 20/50 for the 20-year rotation and 50-acre size of opening.

Table 2 gives information on timber harvest for mode 40/40. Managers may wish to consider this mode for producing biomass on a short period of rotation. While the size of the material harvested would be small, the annual harvest in cubic volume would be close to the maximum. To help evaluate timber yield, a potential timber index (PTI in the right column of the table) has been constructed. PTI is the ratio of annual harvest at any given rotation age to annual harvest at the age of greatest mean annual increment. Yield tables from Schnur (1937) show that the culmination of mean annual increment in cubic volume for Appalachian hardwoods occurs at about age 50 for all site classes. For this example, PTI is computed by dividing the estimated annual yield under a 40-year rotation by the yield at age 50. This index shows managers what proportion of the maximum yield in volume is being achieved.

TIME	OGS VOG	MTS VMT	P1S VP1	P8S VP8	P6S VP6	SAS VSA	PTI VT
E+00	E+00 E+03	E+00 E+03	E+00 E+03	E+00 E+03	E+00 E+03	E+00 E+00	E+00 E+03
.0	150.01 379.47	.00 .00	.00 .00	.00 .00	.00 .00	0. 0.	1.1772 379.47
1.	68.48 498.45	30.97 28.00	.00 .00	.00 .00	.00 .00	0. 0.	1.5463 498.45
2.	29.83 338.04	132.27 170.38	.00 .00	.00 .00	.00 .00	0. 0.	1.7763 572.60
3.	16.26 238.17	183.58 319.58	.00 .00	.00 .00	.00 .00	0. 0.	1.8759 604.71
4.	11.72 196.32	143.15 252.15	.00 .00	.00 .00	.00 .00	0. 0.	1.9206 619.13
5.	7.92 155.43	154.28 281.67	.00 .00	.00 .00	.00 .00	0. 0.	1.9382 625.10
6.	5.39 123.49	118.22 216.46	41.56 9.33	.00 .00	.00 .00	0. 0.	1.9418 625.94
7.	3.67 84.43	90.17 163.11	67.23 72.07	.00 .00	.00 .00	0. 0.	1.9159 617.61
8.	2.73 69.60	77.27 138.13	77.99 100.14	.00 .00	.00 .00	0. 0.	1.8854 607.79
9.	2.37 61.33	73.66 133.47	83.85 104.50	.00 .00	.00 .00	0. 0.	1.8536 599.46
10.	2.15 59.07	69.23 125.57	88.57 234.15	.00 .00	.00 .00	0. 0.	1.8398 592.68
30.	.00 .04	.24 1.26	5.70 19.71	89.15 238.07	65.87 180.38	0. 0.	1.2121 390.19
90.	.00 .03	.16 .83	3.95 13.76	56.72 180.41	135.77 213.59	0. 0.	1.1028 354.85
130.	.01 .03	.13 .68	2.61 9.07	47.32 153.35	116.25 232.04	0. 0.	1.0671 343.98
170.	.01 .02	.12 .65	2.44 7.59	38.23 96.25	119.01 236.75	0. 0.	1.0578 340.99

Table 2.--The 40/40 mode, 40-year rotation, and 40-acre opening. The table contains data for the control of timber sales and information about the volumes of timber expected over time. OGS = old-growth sales (acres/year); VOG = volume of old-growth timber removed (cubic feet/year); MTS = mature timber sales (acres/year); VMT = volume of mature timber (cubic feet/year); P1S = pole-10-inch class sales (acres/year); VP1 = volume of pole-10 timber removed (cubic feet/year); P8S = pole-8 timber sales (acres/year); VP8 = volume of pole-8 timber (cubic feet/year); P6S = pole-6 sales (acres/year); VP6 = volume of pole-6 timber (cubic feet/year); SAS = sapling sales (acres/year); VSA = volume of sapling timber (cubic feet/year); PTI = potential timber index (ratio of timber removed to the amount that would be removed at a steady state 50-year rotation); VT = total volume of timber removed (cubic feet/year). The scales, E + 03, at the top of the table indicate the timber volumes are to be multiplied by 10^3.

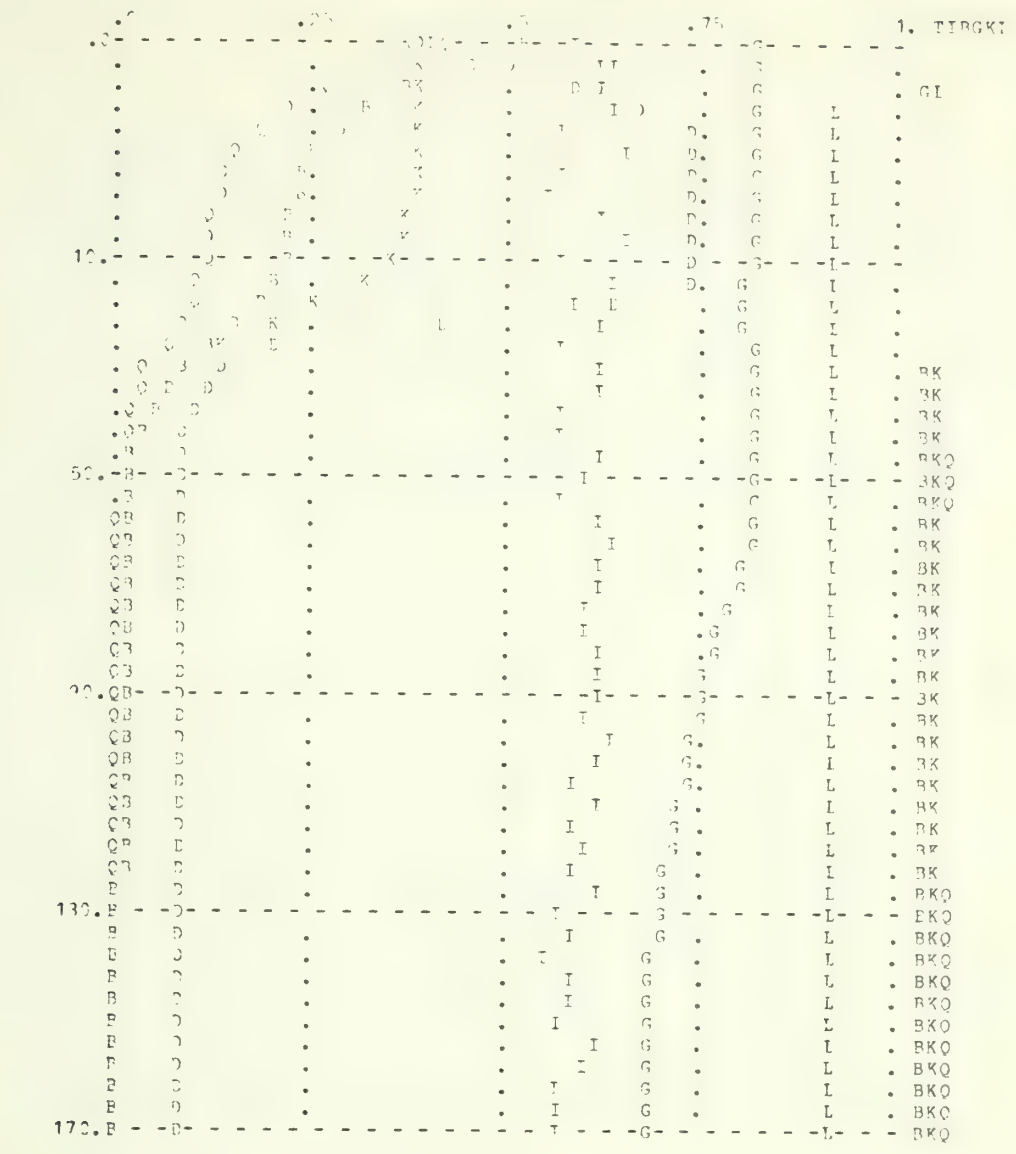
The other columns in table 2 break the timber harvest down by age classes. The model removes the oldest timber first, then timber from successively lower age classes until most timber is being harvested at the designated rotation age and the flow of succession comes to the desired steady state. In table 2, the annual sales from the various habitats are printed annually for the first 10 years, then at 40-year intervals for 170 years. The present sales, year 0, are 159 acres, all from the old-growth habitat (OGS). Only half of this volume is removed because the program includes a 2-year delay for sale and removal of timber. The amount removed (VOG) is 379 x $10^3 ft^3$ for all trees 0.6-inch diameter and larger, inside bark, stump to tip. The next year, time 1, old-growth removals (VOG) are larger because of the carryover from the initial sales. Old growth is not liquidated until after the 10th year because some mature timber is succeeding into old growth each year. By time 170, no sales are being made from the old growth (OGS), while only a negligible amount of harvest is from mature timber (MTS) and 10-inch pole habitats (P1S). Most removals are from the 8-inch pole (P8S) and 6-inch pole (P6S) habitats. No timber has been removed from the sapling habitats (SAS).

The potential timber index (PTI) is greater than 1.2 until after time 50. As the older stands are liquidated, large volumes (VT), as much as 625 x $10^3 ft^3$ at time 6, are removed. At time 170 the potential timber index is about 1 and removals are about 340 x $10^3 ft^3$. At this time the distribution of habitats approaches the steady state distribution for a rotation period of 40 years.

A comment is required to explain why the harvest at steady state is removed from both the pole-6 and pole-8 habitats rather than only from the pole-6 habitat at exactly 40 years of age. All removals for this mode could be mathematically forced to occur at 40 years, but this would model an improbable situation in the forest. The reality is that trees grow at a variety of rates on any selected area of reasonable size, because species and growing conditions will vary and cannot be precisely predicted. The model allows for variance in size by supposing that some portion of a size class will be harvested a short time before and after the specified rotation age. It does not attempt to distinguish between site classes. The estimates of volumes provided by the model do, in fact, compare very well with estimates of volumes obtained by specifically controlling combinations of site classes for an assumed area of harvest and rotation age (Schnur 1937). However, estimates of volumes from the model are not intended to be precise predictions of future yields but rather realistic approximations to be the basis for selecting a mode of management.

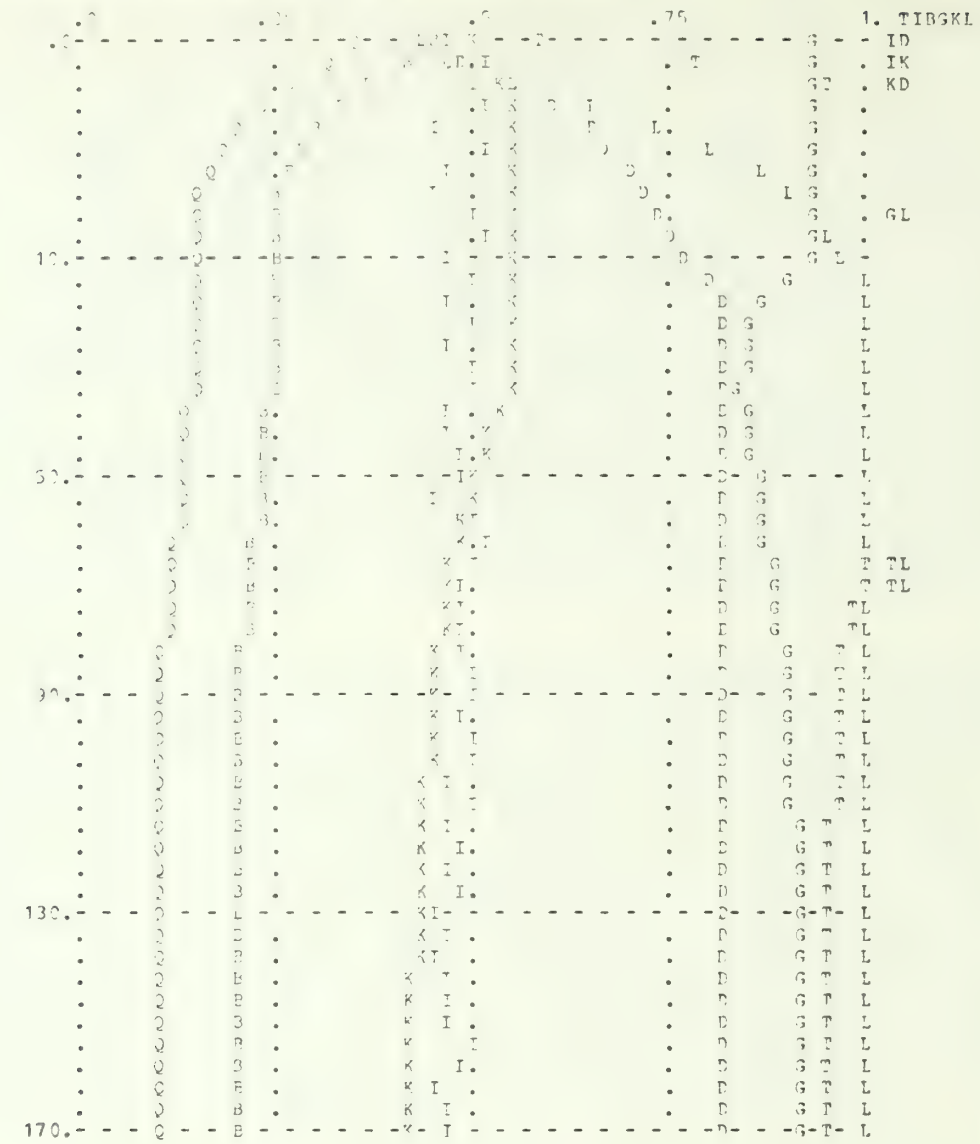
Once the distribution of habitats for the future has been modeled, we can derive indices for timber-related benefits and negative consequences or impacts. For the modes 40/40, 80/25, and 160/10, seven benefits and one impact are illustrated in figures 1, 2, and 3. The indices are computed with algorithms, supplementary equations which express relationships between benefits and the distribution of habitats in the forest (chapter 5).

All benefits and impacts are scaled from 0 to 1 to provide for relative comparisons. The value 1 represents the production of a particular benefit if management favored that benefit over all others. For impacts, the value 1 represents the undesirable limit. Zero is the minimum for benefits and impacts. The potential timber index is not on the plot for 40/40 because the value exceeds 1 (table 2). The values for bluebird (L), bear (B), grouse (G), deer (D), squirrel (Q), and turkey (K) represent the quality of habitat for these animals and associated species. Sediment (I) is an index of the expected movement of sediment, assumed to vary with the amount of roads constructed.

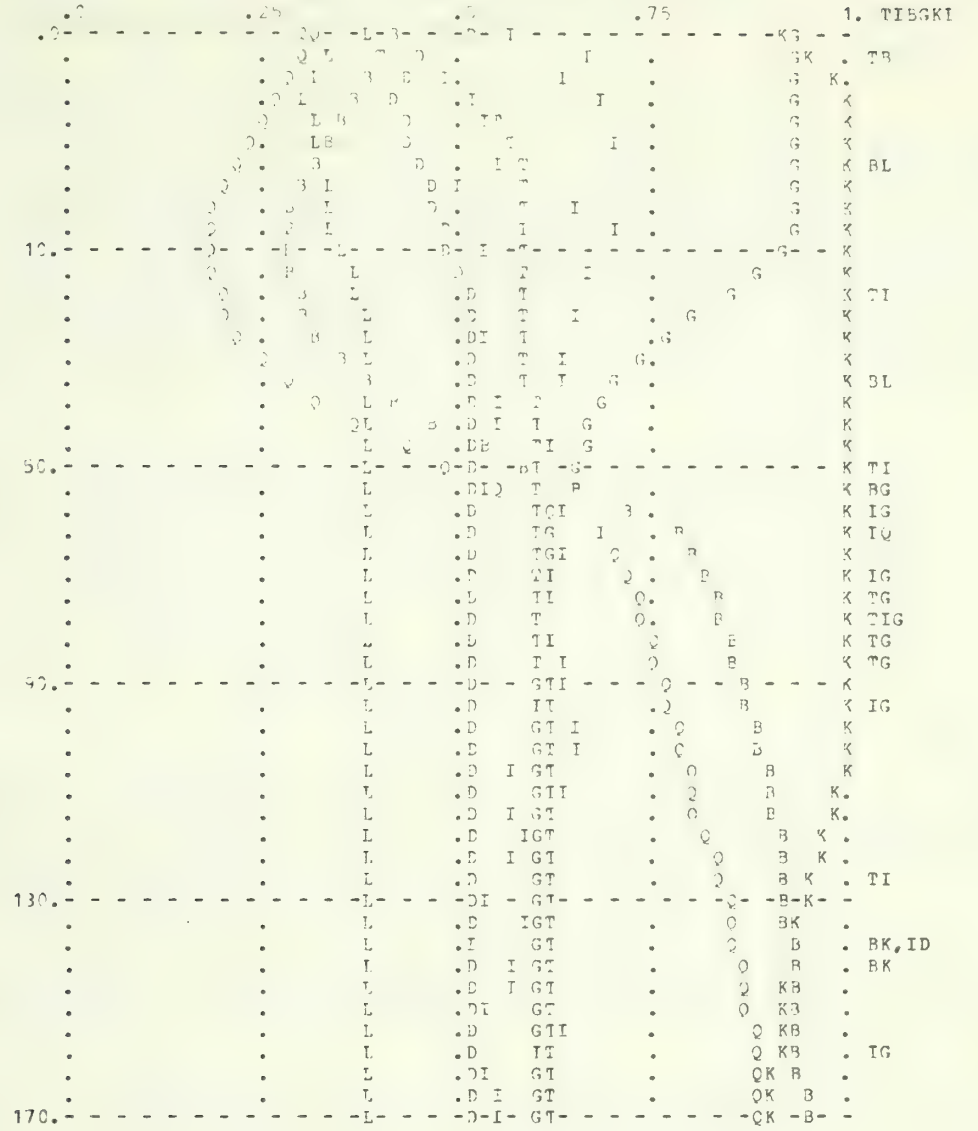


Figures 1, 2, and 3.--Plotted outputs of indices for seven benefits and one impact for three modes of management. T = potential timber index; I = sediment; B = bear habitat; D = deer habitat; Q = squirrel habitat; L = bluebird habitat; G = grouse habitat; K = turkey habitat. Indices are plotted annually for the first 10 years, then at 3-year intervals. Letter groups at the top of the graph indicate coincident indices; the first letter of each group appears on the plot.

PTI=I,SEMT=I,BEAL=D,...=...,IDT=...,PLD=I,DRAW=D,SQ=0



PTI=T,SEMI=I,BLAS=B,SPA=S,IND=K,FLD=L,ORDER=O,SPD=Q



After 40 years the mode 40/40 has removed most of the trees in the age and size classes for producing hard mast, so the habitat indices for squirrel, bear, and deer are reduced to low values (fig. 1). The indices for grouse and bluebird are high and sediment is well below the unacceptable value of 1.

A change to the mode 80/25 (fig. 2) doubles the length of the rotation period and reduces the size of the openings to 25 acres. The indices for all of the animals are increased, although the indices for bear and squirrel are still quite low. The sediment index has declined slightly. The potential timber index (T) exceeds the value of 1 until time 66, then declines to 0.95 by time 170. The 80-year period of rotation brings the removal of timber to about the same value as a 40-year rotation but with more volume being removed per unit area, larger trees being harvested, and more timber-related benefits being produced. Thus in both the short and long run, the longer rotation may yield economic advantages over the 40/40 mode.

A change to the mode 160/10 again doubles the length of the rotation period and reduces the size of openings to about 10 acres. The index for sediment is still within acceptable values; the index for bluebird has declined to about 0.4 and indices for the other animal habitats are above 0.5 (fig. 3). The rotation period is now four times that of the mode 40/40, yet the potential timber index (T) is still a respectable 0.6. At this longer rotation the trees harvested would be expected to have a higher value per unit volume than trees harvested from either mode 80/25 or mode 40/40. For some ownerships, returns from the related benefits may more than compensate for the reduced volume of timber harvested.

The original distribution of habitats found in the inventory of the forest is not congruent with any of the illustrated modes of management at the steady state. Consequently, in the first 40 to 100 years there is considerable change in the combinations of benefits produced as the distribution of habitats and benefits is brought to a steady state. Different management modes require different times to reach a steady state. The combinations of benefits at stability are the combinations revealed to be biologically possible for long periods, possibly hundreds of years. The distribution of habitats at the steady state is the goal for management for that particular mode.

Deviations from the projected course are detected in the periodic inventories. Typically, 10-year inventories are used to adjust the management system to the real forest systems. Rotation periods and sizes of openings are changed for each succeeding decade to correct for unexpected changes in the distribution of habitats that may result from cultural actions, wildfires, land use changes, changes in the markets for timber, and losses from insects and diseases. The inventory is part of a negative feedback loop that functions at each inventory period to keep management actions directed toward the goal.

1.4.4 The Basis for Decisions

DYNAST-TM provides information in easily read charts and tables as a basis for making decisions. The primary decision is to select a mode of management that produces a regular flow of timber and related benefits in amounts to yield, over long periods of time, raw materials for industry and acceptable returns on investments. The computer runs make explicit the trade-offs between various periods of rotation. DYNAST-TM relates the production of timber to other benefits so that managers can choose the

combination that best meets the objectives of the forest business. All levels of management can participate in the decisions, and the probability of "correct" decisions can be greatly increased (Beer 1966). As the mode of management is applied, actions are ordered and interrelated because they are directed toward the single goal of bringing about and maintaining a certain distribution of habitats at a steady state.

1.5 Relation of the DYNAST-TM Model to Classical Systems of Silviculture

The DYNAST-TM model does not attempt to model any of the classical systems of silviculture that are described by Troup (1952), Hiley (1954), Davis (1954), Smith (1962), Assmann (1970), and U. S. Department of Agriculture, Forest Service (1973).

Rather, DYNAST is a method which includes and perhaps supersedes these systems. DYNAST-TM explores the consequences of manipulating the period of rotation and size of opening. Actually, the classical systems of silviculture can be described by these two variables, as modified by in-place enhancements (sec. 3.7). Properly considered, such apparently antithetical methods as "clearcutting" and "selection" appear as points on a continuum. Removing a selected large tree leaves a small opening in the forest; clearcutting a tract leaves a large one. Likewise, the "shelterwood" system of silviculture can be analyzed into rates of harvest, size of openings, and delays in removal.

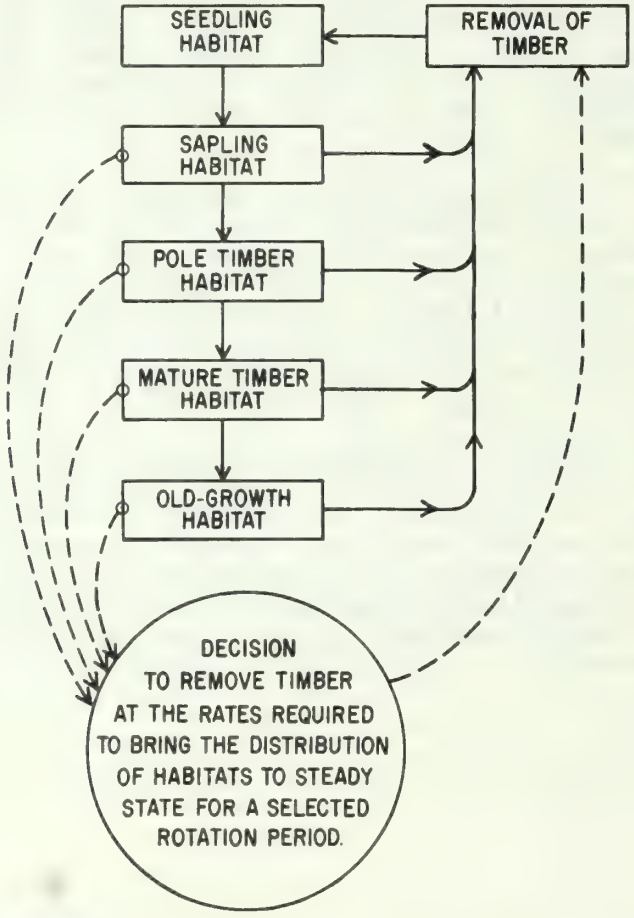
Other features by which the classical systems of silviculture are classified seem to be based on erroneous assumptions. We speak of "high-forest" methods, supposed to produce stands grown from seed, and "coppice-forest" methods, supposed to produce stands from sprouts. But in the real forest, naturally regenerated stands invariably contain trees originating from both seeds and sprouts. Sprouts can grow into tall, dominant trees. Likewise, we speak of "even-aged" versus "uneven-aged" management, but except for plantations, there are no even-aged stands.

The dynamically analytic silviculture technique replaces all the classical silviculture systems. DYNAST is not limited by arbitrary and inaccurate categories, but provides a continuum of possible silvicultural actions. DYNAST-TM can examine thousands of possible combinations of rotation periods and sizes of openings, while DYNAST-MB allows the assessment of the wider range of benefits produced under a two-rotation system. DYNAST directs attention to the biologically possible combinations of benefits that can be provided in perpetuity by harmonized management actions.

The core of the DYNAST-TM system is a dynamic model of the distribution of habitats (age classes) in the forest as modified by harvest of timber. The model has a cybernetic structure; it is arranged to guide the forest toward a goal through a set of negative feedback loops. The goal is to achieve a given distribution of habitats and maintain it in a steady state, thereby producing a constant flow of timber and related benefits in the desired combination. The feedback mechanisms control the removal of timber to create a steady flow of land into seedling habitat, thus regulating the proportions of different habitats in the forest of the future.

Figure 4 presents a simplified version of the DYNAST-TM model. This diagram suppresses time delays, accounting processes, and certain feedback mechanisms regulating the flow of succession into the old-growth state. The complete model is described mathematically in chapter 4.

Figure 4.--A simplification of the DYNAST-TM model. Solid lines represent flows of succession and harvest. Dotted lines represent flows of information which affect decisions. Time delays and other features are omitted.


SEEDLING HABITAT
REMOVAL OF TIMBER
SAPLING HABITAT
POLE TIMBER HABITAT
MATURE TIMBER HABITAT
OLD-GROWTH HABITAT
DECISION TO REMOVE TIMBER AT THE RATES REQUIRED TO BRING THE DISTRIBUTION OF HABITATS TO STEADY STATE FOR A SELECTED ROTATION PERIOD.

The central sector of the model monitors the flow of succession through the classes of habitat. Time delays for each stage of growth must be fed in for the area under study. (For example, in the Southern Appalachians, 5 years are allowed for the transition from seedling to sapling habitat.) The model can then project the distribution of habitats for any point in the future and estimate the combination of benefits the forest will yield. More importantly for the structure of the system, the model senses the current

distribution of habitats and, through its feedback loops, makes adjustments to guide the managed forest toward the desired equilibrium.

The model is structured to bring the forest to a certain distribution of habitats and sustain that indefinitely. First, managers select a period of rotation to be screened by the DYNAST system. The model then computes the annual area of harvest by the conventional method for area control (Forbes 1961, sec. 4) in which the total area is divided by the period of rotation. It determines the distribution of habitats which will prevail at the steady state, then guides the forest toward this goal through a set of negative feedback loops that regulate the area to be harvested annually from each age class (fig. 4). During the transition period, the oldest stands are harvested first. At steady state, the harvest will, of course, come from the oldest one or two age classes permitted by the chosen period of rotation.

For each year, the model fills the annual harvest from selected age classes. Eventually it will liquidate the habitats which are older than the selected rotation age. The remaining habitats will be brought into balance to assure an even succession for the future. Harvest of the older habitats may be temporarily restrained in order to bring about this balance.

By comparing model runs, managers adjust periods of rotation and sizes of openings for a regular flow of benefits in amounts to provide acceptable returns on investments. However, this is not a one-time decision but rather a sequence of evaluations. The structure of the model provides for a continuous, dynamic analysis of benefits expected and for periodic adjustments in periods of rotation and sizes of openings.

This flexibility is one of the chief advantages of the dynamic modeling technique. Changes in markets, disturbances in the forest, and changes in the relative value of benefits have produced frequent changes in rotation periods. Long-term goals are best defined in terms of a steady state, but, in fact, forest managers work with an unending transition period. Earlier estimates of timber yields during the transition periods were cumbersome and difficult, sometimes requiring 20- to 50-yard rolls of graph paper (Forbes 1961, sec. 4), and this procedure would have to be repeated after every disturbance or change of policy. The structure of the DYNAST-TM model provides for changes and makes analyses of expected benefits during the transition periods relatively easy, while at the same time providing information on the expected combination of benefits at the steady state.

When DYNAST is used to predict the consequences of a given mode of management, it simply computes the indicated rates of harvest for each year and integrates them into its projection of the future state of the model forest. When the system is being used to guide the management of a real forest, managers would read out the indicated sale of timber and then select tracts for harvest during the year. However, since the modeling process can never be perfect, inventories and controls must be continuously used to keep the model forest in touch with the real forest and with changes in demands for benefits. In the core model, the time delays in the flow of succession and in the practical harvesting process must be compared with experience; in the algorithms for estimating benefits, the relationships must be continuously updated by the findings of researchers; and in the overall choice of a combination of benefits or a mode of management, the changing values of benefits may modify the policies chosen in the past. Ultimately, acceptable returns on investments and human knowledge guide the management of the forest.

2.2 Estimating Benefits

The DYNAST core model predicts what distribution of habitats, or age classes, will follow from a given mode of management. This part of the system is applicable to many, perhaps to all, types of forest, needing only to be supplied with growth rates (successional delays) for the locale or perhaps with a different classification of habitats than the seven that were chosen for the eastern hardwood forests. However, the part of the model that estimates benefits is specific for a given type of forest.

The availability of benefits depends on the state of physical organization of the forest--the proportions which are covered by seedlings, saplings, pole timber, mature timber, and old growth. Algorithms, or statements of relationship, must be constructed to express how a particular benefit depends on the distribution of habitats. The current version of DYNAST-TM incorporates 17 algorithms for estimating benefits in eastern hardwood forests. The algorithms are written as nonlinear supplementary equations. An algorithm may be added, deleted, or changed without affecting the core model or the other algorithms; thus this part of the structure is quite flexible and may be readily adapted to different circumstances or modified by new knowledge from research or inventories.

The particular relationships assumed between habitats and benefits must always be regarded as tentative and subject to revision. For a start, we can derive a set of algorithms from current practical and scientific knowledge of forestry and forest ecology. As the system is applied, these assumed relationships would be tested by measuring the production of benefits in the real forest, and they would be adjusted to fit a particular area. New algorithms could be added as changing social needs focus interest on a different set of benefits; for example, algorithms could be constructed for fuelwood, biomass, and chemical wood. The model is a dynamic management structure through which new knowledge from research and experience can be used to improve decision-making.

The following sections offer a general explanation of some of the algorithms now used in DYNAST-TM. For the equations and a fuller explanation of how the algorithms were derived, see chapter 5. For the scaling of indices, see section 1.4.3.

2.2.1 Timber

The algorithms for timber production yield a potential timber index, which is the ratio of the volume predicted for harvest to the volume that would be expected if timber production were favored over all other benefits. For the Appalachians, a rotation of 50 years is assumed to produce the maximum yield of cubic volume of merchantable wood (Schnur 1937). The model estimates productivity under a 50-year rotation and compares it with productivity for a given mode of management, with its specified rotation period and size of openings. The algorithm includes a factor which reduces estimated yield where small openings are required, because cutting timber in a small area causes disproportionate damage to surrounding trees and because the growth of young trees is slow in a small opening. Published studies of timber volume per acre for the different age classes supply data for the computation.

2.2.2 Wildlife

The model incorporates algorithms for the major game species of Appalachian forests and for several other arbitrarily chosen, but representative, species. In each case, the algorithm states a relationship between the distribution of age classes in the forest and the species' habitat requirements. For example, the index for white-tailed deer has a high value when many small areas of seedling habitat are dispersed in an area which also has substantial stands of large pole and mature timber. Seedling habitat contributes soft mast and forage, while 10-inch pole timber and mature timber are the most bountiful producers of hard mast for winter food. The deer index rises toward the maximum of 1 as seedling habitat increases up to 7 percent of the total area; these are assumed to be optimal proportions within the practical limitations of multiple-benefit management. Deer can probably use seedling browse more effectively when it occurs in small, well-dispersed openings; therefore, the deer index rises as opening size diminishes toward 6 acres. Beyond these limits, assumed to be optimal, the contribution of a factor to the index levels off; in the model, 1-acre openings are no better for deer than 6-acre openings. In similar fashion, algorithms relate the requirements or preferences of other animals to the distribution of habitats in the forest.

Wildlife researchers have established the general habitat requirements for many species, and data from published research underlie all the algorithms described in chapter 5. However, many of the quantified relationships, especially the optimal proportions of different habitats and the optimal size of openings, are based on fragmentary or inconclusive data and will need to be revised in the light of future research. Indeed, one of the virtues of the DYNAST system is that it provides conditions for studying the relation of wildlife populations to different combinations of forest habitats. In turn, the system is refined by the research which it helps to foster.

2.2.3 Sediment Flow

Particles of sediment flow through the landscape at varying rates, affected by the steepness of slopes, wind, the movement of water above and below ground, and the kinds of geologic substrate. Forests retard the flow. The flow rates of both organic and inorganic particles are delayed by the matrix of roots and soil and by the protective cover of leaves, branches, and other litter. Trees can be removed from the forest with relatively small increases in the flow of sediment if the protective layer of litter and the surface matrix of roots and soil are not destroyed. Road building, which breaks up the surface layer, is the most important cause of increased sediment flow.

A practical index of sedimentation can be based on the number of openings formed per square mile of forest per year. The number of openings is an index of the number of miles of roads and skid trails required to remove the timber (Nyland and others 1976). As the size of openings decreases, the number of openings for equal areas of harvest increases. However, where there are many small openings, the miles of roads and skid trails required per opening may be reduced by clustering the openings. Thus, the relationship between the openings per square mile and the silt production is not a straight line; as the number of openings increases, sedimentation increases, but at a declining rate (fig. 5).

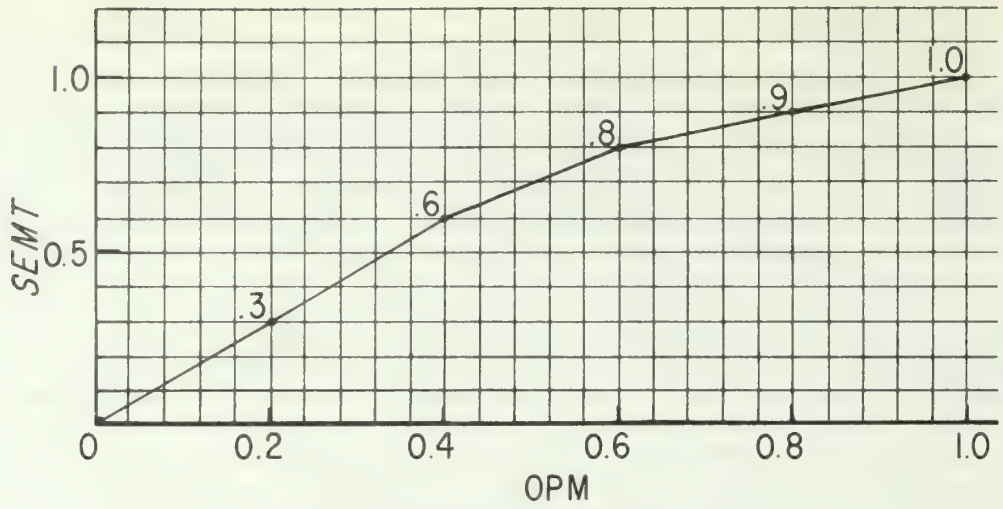


Figure 5.--The indicated flow of sediment (SEMT) versus the number of openings formed per square mile of forest (OPM).

For typical modes of management, the number of openings per square mile normally varies between 0.2 and 0.6. The unacceptable limit of 1 on the index scale is reached when one new opening per square mile per year is formed, while an index of 0 indicates that no openings are being formed. Although considered "unacceptable" for management purposes, the movement of sediment at the index value of 1 is still much smaller than losses from most other kinds of land use (U.S. Environmental Protection Agency 1973; Oertel 1974).

2.2.4 Esthetics

Trying to measure the beauty or ugliness of a landscape may be a fruitless enterprise, and certainly the normative judgment implied in scaling an esthetic index from 0 to 1 can reflect, at best, only a consensus of subjectivities. However, because the appearance of a forest is certainly related to its distribution of age classes, some elements of forest esthetics may be quantified and modeled. DYNAST-TM incorporates algorithms for "ugliness" and "visual variety" (sec. 5.5).

The raw, disorderly appearance of recently harvested timberland is the subject of the ugliness index. This index integrates the total area in seedling habitat, the frequency of openings, and the size of openings. As any of these increases, the ugliness index increases. The unacceptable limits which define a value of 1 are a 6 percent fraction of seedling habitat opening size averaging 30 acres, and openings formed at the rate of one per square mile per year.

Variety and contrast are important criteria for assessing the visual appeal of a forest environment (Larson 1971; Zube and others 1975). Within the topography of any landscape, the distribution of forest stands of contrasting heights can affect visual appeal. The index for visual variety distinguishes three height classes: young stands over 50 feet, mature and pole timber stands over 50 feet, and tall, flat-topped, old-growth stands. The index rises toward the maximum of 1 when these classes are in balance, each occupying 30 to 40 percent of the total area, and when seedling habitat is at the minimum (4 percent) required to maintain the balance of the three size classes in the future.

2.2.5 Other Algorithms

The model also includes algorithms for gray squirrel, turkey, ruffed grouse, and black bear habitat; for four woodpeckers; and for four songbirds, bluebird, towhee, ovenbird, and pewee, which represent groups of birds with different habitat requirements. There is no algorithm for water volume or for nutrient flow. Hydrological research for the Appalachians suggests that only the shortest periods of rotation will materially affect the annual runoff of water and nutrients. We simply do not know enough at this time to be able to model the flows of nutrients with any precision. A nutrient index remains a possibility for the future, however, and it would be important in relating patterns of timber harvest to the long-term fertility of the forest environment and to the nutrients entering streams. These questions are explored in sections 5.13 and 5.14.

3. IMPLEMENTATION OF THE DYNAST-TM SYSTEM

3.1 The Choice of a Mode of Management

To apply the DYNAST-TM system, managers would first screen a series of modes of management for their estimated production of timber, related benefits, and impacts. The model is prepared for the trial screenings by providing it with successional delays for the area under study and with definitions of several modes of management. If the algorithms for estimating benefits are unsuitable for the purpose, new algorithms may be constructed and inserted. After the trial runs are evaluated, further screenings of intermediate modes of management may be tried until a mode of management is found which produces the desired combination of benefits.

Once a mode of management is chosen, it is applied by selecting areas for harvest from the habitats, and at the rates, indicated by the model run. After the systematic management of a real forest is underway, frequent inventories and continuous research will be needed to adjust the modeling process to the dynamics of the real forest.

The modes of management are determined by three kinds of constants that are listed in table 1. The first constant (ROT) determines the period of rotation for timber harvest. The remaining two constants (ISO, ISD) determine the average size and variance of openings desired.

The number of possible modes of management is very large. For example if we consider ten different values for each of three constants (ROT, ISO, ISD), the number of modes for consideration is $10^3 = 1{,}000$. This enormous variety can be reduced by examining extremes and a sample of intermediate modes. An initial combination of six modes is suggested in table 1. After examining the combinations of benefits and impacts from these modes, one may want to examine a few other modes. The process of trial and examination continues until a mode is found that provides the most desirable combination of timber and related benefits.

Procedures for improving the precision of management decisions for a given area and for adapting the DYNAST system to a different area or different kind of forest involve essentially the same procedures and will be described together.

The DYNAST system is relatively easy to use and to adapt to areas different from the example. The amount of information required for the first period of operation is minimal. During successive periods, repeated adjustments improve precision until the management system is adapted to a specific area of land. The essential information required for the first period of operation is:

--An accurate inventory of the distribution of habitats.

--Information about the rate of succession and the reliability of natural and artificial regeneration after harvest.

--A set of algorithms which relates benefits to the distribution of habitats and the sizes of openings formed by harvesting.

3.2 Inventories and Management Decisions

The first step is to obtain an accurate inventory of the area covered by each type of habitat. Existing inventories by age class (5-year increments) or by size class (1- or 2-inch increments) may be converted into the classification defined in section 1.4.2. If data are not already available, some kind of inventory method must be used (Husch, Miller, and Beers 1972). Permanent control plots, if obscurely marked so they will not receive special consideration, are probably a most effective method over a long period of time.

Inventories should be repeated at intervals, possibly 10 years, that keep differences between the model and the forest within acceptable limits. One use of repeated inventories is to adjust the control constants (sec. 1.4.3) and to change the coefficients for delays in succession in the model. Secondly, the inventories provide information essential for evaluating the performance of the management system. Information for management decisions should not be confused with the validation of algorithms for estimating amounts of benefits (sec. 3.5) nor with the evaluation of in-place enhancements (sec. 3.7). Inventories should be totally independent of any information collected for use in assessment of benefits and impacts and any information used to make in-place enhancements.

To maintain this distinction, these inventories for management information and decisionmaking should be the responsibility of an inventory unit of central management (Beer 1966). These inventories should be limited to collecting information needed to evaluate and refine the functioning of the core model: the delays for succession, the rotation age for maximum timber production, the model's running estimate of the proportionate distribution of habitats, and the coefficients defining the mode of management. For an example of the use of these constants, see the C-cards listed at the end of the list of equations in appendix A. The essential information is given in equations 168.4,C through 168.7,C with attached definitions.

3.3 Delays for the Flow of Succession

The delays for successional change must be estimated from historical data. For the Appalachians, the most extensive information comes from Schnur (1937), the unpublished reports of Frothingham,[1/] reviews of research, and data from the Forest Survey (Knight 1978). These data are used to develop the relationship of age to median diameters at the junctures for classes of habitats (fig. 6). The average delays for successional change are initially determined from this relationship. For the Appalachians, the average delay for seedling habitats is 5 years. On some areas the time may be 6 to 7 years, and on other areas it may be as low as 3 years. The successional delays for sapling habitats are 30 years; for pole-6 and pole-8 habitats, 15 years each; for pole-10 habitats, 20 years. The total time required to grow mature timber is 85 years. These constants are used to model the successional change from harvested areas to mature timber habitats. Errors in these constants for a specific area are to be corrected with information from each successive inventory.

1/ Frothingham, E. H. 1917. Report on study of cut-over areas in the Southern Appalachians. Unpubl. Mimeogr. 229 p.

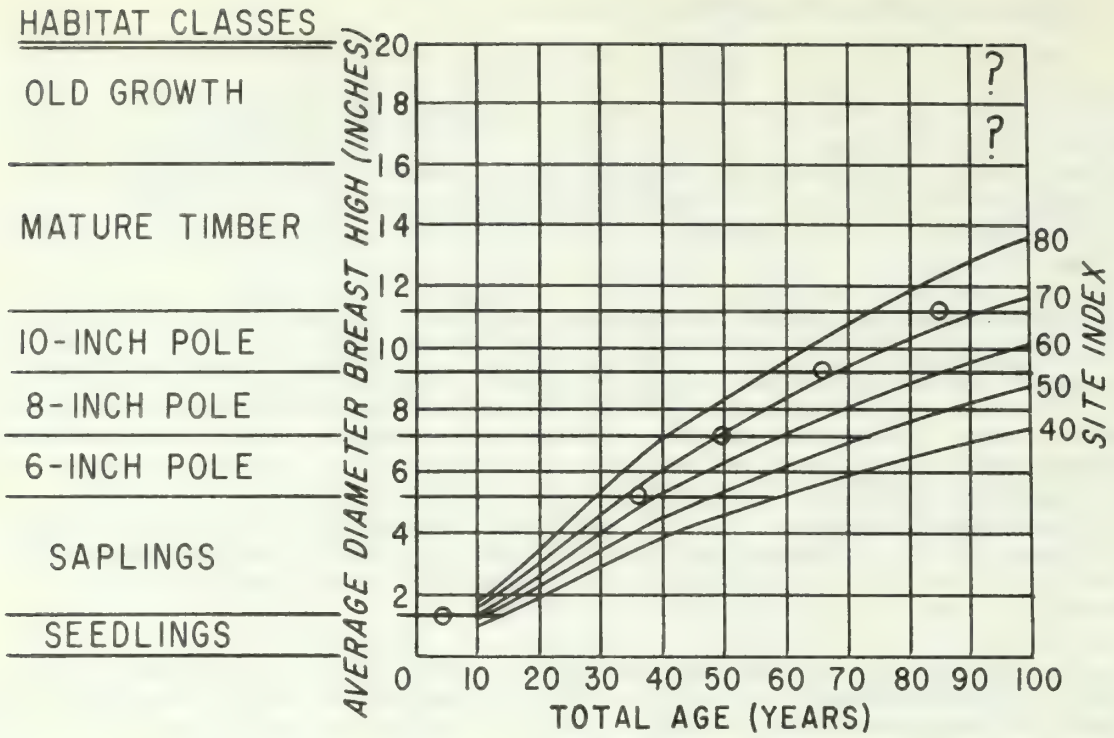


Figure 6.--The relation of habitat classes to age. (Modified from figure 6, Schnur 1937.)

3.4 Development of Algorithms for Benefits

From the theory for multiple benefits (Boyce 1977, sec. 4.5), the proportional distribution of habitats determines the kinds and proportions of multiple benefits available from the forest. At any given moment in the model run, the relative amount of a particular benefit is estimated by algorithms. These are written as supplementary equations to the model for management. The algorithms are independent of each other. They do not influence the core model for succession and harvest and they are totally dependent on the distribution of habitats and the size of openings.

Information for developing algorithms is derived from research and experience. The turkey index will illustrate the method for building an algorithm. A long list of the turkey's habitat requirements is given in the Wildlife Habitat Management Handbook, chapter 401 (U.S. Department of Agriculture, Forest Service 1971). Because the enormous variety of items listed could not possibly be controlled by management actions on millions of acres, the least important items and those that cannot be directed were removed from the list. The items that remained were those important indicators of turkey habitat which are affected by patterns of timber harvest.

This analytical process resulted in the selection of hard mast, forage, soft mast, seeds, insects, snails, and cover. All of these variables can be expressed by two forest conditions: the size and distribution of openings and the proportion of area in mast-producing forests. From the Wildlife Habitat Management Handbook, chapter 200 (U.S. Department of Agriculture, Forest Service 1971), hard mast is most abundant in stands averaging 8 to 16 inches in diameter. With this information a curve can be drawn on a piece of graph paper (fig. 7) that expresses this assumption: as the proportion of area in

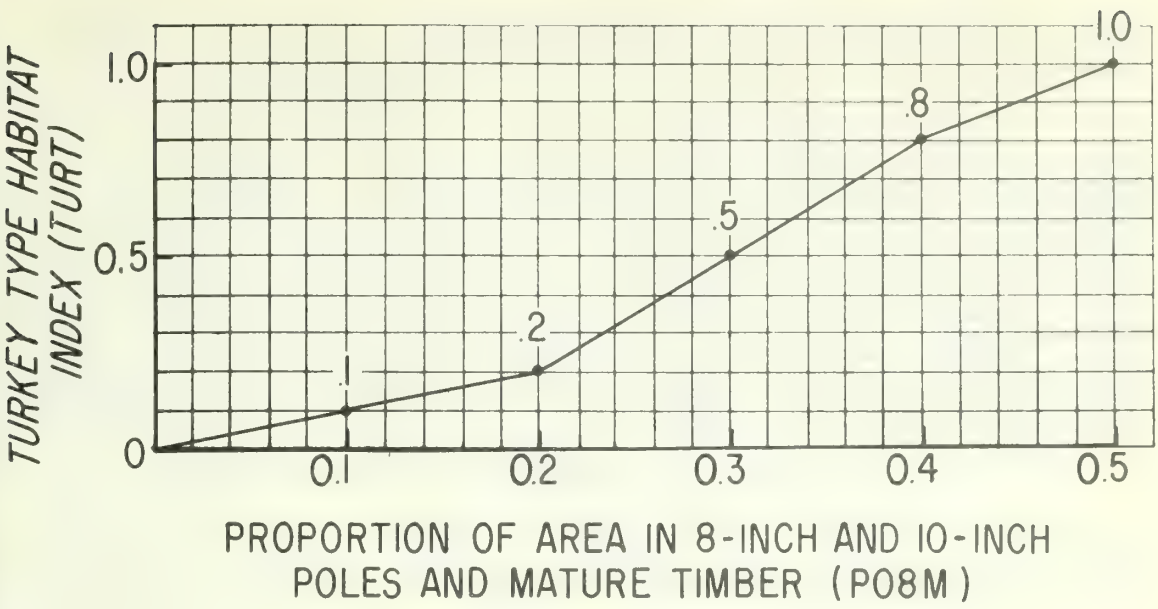


Figure 7.--Turkey-type habitat index versus the proportion of area in 8-inch and 10-inch poles and mature timber.

hard-mast-producing habitats increases, the quality of habitat for turkey increases. But there is a limit to how much of the forest can be kept in pole and mature timber when the distribution of habitats is brought to a steady state. A few calculations showed that only about half of the forest can be maintained in these states at equilibrium; this is a biological limit. The optimum quality of turkey habitat was set at this limit (fig. 7). The turkey habitat index is 1 when half of the forest is producing hard mast and 0 when none of the forest is producing hard mast. The next step was to determine the shape of the curve between 0 and 0.5. This curve must be based on experience, on whatever can be found in publications, and on the biological constraints when the forest is at different steady states. The shape of the curve will later be refined by periodic assessments and validations (sec. 3.5).

The size and frequency of openings are computed as supplementary information by equation 94,S. In the index for opening type for turkey, the assumption was: both very small and very large openings have low value for turkeys. Some range of opening sizes must represent an acceptable quality of habitat for turkeys. This assumption was expressed as a graph (fig. 8). When the most frequent size of openings is less than 10 or greater than 16, the index for turkey opening type declines. Finally, the indices for mast and openings are multiplied together. The result of this analysis is an index that indicates the quality of turkey habitats as the organization of the forest changes.

It is not necessary to be concerned with how much area is in sapling stands, which provide cover, because this state will always be satisfied whenever the turkey index is relatively high. The same is true for soft mast, seeds, insects, and snails. Another limitation not covered by the turkey index is the need to distribute seedling habitats by removing some timber during each 5-year period from every tract of about 600 to 1,000 acres. This is an example of an in-place decision (sec. 3.7).

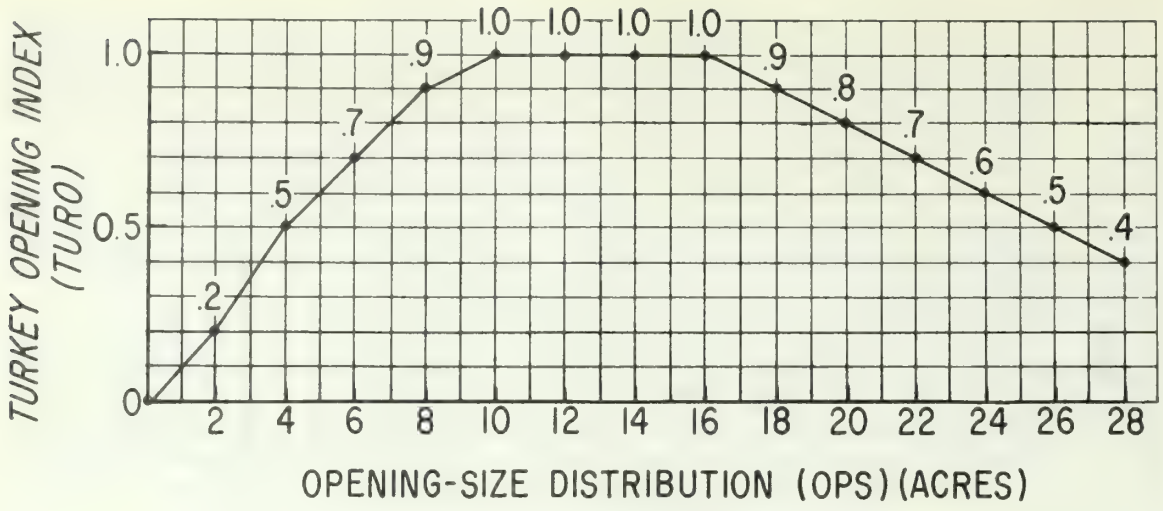


Figure 8.--Turkey opening index versus the distribution of size of openings (OPS).

A very large number of benefits and impacts may be expressed as algorithms; those of interest are the ones that provide a basis for selecting a management mode. Each algorithm may be adjusted with new experience and research data to reflect more closely the real forest. Again, adjustments in one algorithm do not affect other algorithms, because they are independent of each other.

3.5 Validating the Algorithms

Initially, algorithms are developed from information derived from research and experience. Later, they are assessed according to data collected from the real forest and then modified for a specific area. The assessments and the modification of the algorithms should be made by well-trained and experienced specialists and kept totally separate from the inventories (sec. 3.2). The purpose of the assessments is to develop algorithms that provide a rational basis for management decisions to modify the mode of management.

The algorithms are assumed relationships with parameters derived by statistical analysis from experimental data and experience. The statistical analyses are available in the scientific literature as fragments of the dynamic behavior of the forest.

There are several difficulties in deriving algorithms from published research: differences in biometric techniques, differences in results among studies, and the inability to relate research results to the states of forest organization. These difficulties can often be resolved by using the relationships that closely fit the experience, observation, and descriptive knowledge of forest managers. In this way the validity of each algorithm is based on experimental evidence and tempered by practical experience. The system provides for changing the assumed relationships as new knowledge becomes available. The use of nonlinearity in the assumptions allows us to

closely fit the relationships to the results of research and experience. A more detailed discussion of nonlinear relationships may be found in Wagner (1975, p. 525) and Forrester (1961).

Some aspects of the algorithms are more sensitive than others. Research aimed at validating or adjusting the algorithms should begin by focusing on these sensitive points. Again, the turkey habitat index serves as an example. From the assumption about opening size and frequency (fig. 8), it is readily apparent that, when the most frequent opening size (OPS) is less than 8 acres, changes in OPS change the index rapidly; when openings are larger than 16 acres, the index is affected only moderately; and when openings are between 10 and 16 acres, the index is not affected by changes in OPS. Thus, as the algorithm has been constructed, the opening size range of 0-8 is most sensitive to change. When research undertakes to adjust the algorithm according to turkey production in a particular area, refining this sensitive sector of the curve will have the greatest effect on the output of the model.

An important point is that the validity of the algorithms for benefits and impacts will be determined by how well research and experience can continue to develop relationships and relate them to the states of organization of particular forests.

3.6 Starting the Model and Making Sensitivity Tests

The model is started by inserting an inventory of the distribution of habitats. This information is entered into the model as the control constants ISE, ISA, IP6, IP8, IP1, IMT, and IOG (Eq. 168.5,C).

The values for rotation periods (ROT) and for sizes of openings (ISO $\pm$ ISD) are selected for any array of management modes that are to be examined for a desired combination of benefits (table 1). The values for ISD are determined by choosing the maximum desired deviation from size of opening (ISO) and dividing this value by 2.4 which is the limit in the normal deviate function, NORMRN (Eq. 168.7,C).

The delays for succession (DSE, DSA, DP6, DP8, DP1, DMT, DOG) are derived from research and observation. They are changed only when there is reliable, new evidence to adjust the age and diameter relationship (sec. 3.3) for the specific area under management.

TMR is the rotation age that maximizes the production of timber. It must be specified for the particular area under management (sec. 5.1). Typically, it is the age when mean annual increment peaks. This age varies according to whether one wishes to consider saw logs, pulpwood, or total cubic volume.

Once the model is supplied with control constants and successional delays for a particular area, tests should be run to determine the sensitivity of the model to the various changes. These tests have two functions: to identify any areas of weakness in the logical structure of the model and to identify areas in which research needs to be concentrated.

One kind of sensitivity test is to make large changes in the control constants for the mode of management. If the resulting change in output seems unrealistic, or if the model becomes unstable, there may be an error in the structure of the model. Such errors can normally be corrected by referring to the diagrams and the information networks described in chapter 4 and the list of equations (appendix A).

Another kind of test is to observe the effects of small changes in the delays for succession upon the modeled distribution of habitats and production of benefits. If the changes in output are large, this might conceivabl reflect a defect in the model, but more likely calls attention to a real and important property of the biological system. For example, if reducing the relay for succession of seedling habitats from 5 to 3 years greatly affects the timber production and wildlife habitat, then research is urgently needed to determine the exact successional delay for seedling habitat in the area under study.

Thus, sensitivity tests serve not only to determine whether the model reflects the dynamics of the forest, but also to help identify needs for specific assessments and research.

3.7 In-place Enhancement of Habitats

Many cultural actions are opportunistic, in that they depend upon the state of the forest, the availability of investment funds, local markets, or demands for certain benefits. Some examples are thinning, pruning, leaving den trees, making water holes, locating trails, applying fertilizers, and weeding. Such measures, because they are planned by someone on the scene, are called in-place. These actions cannot be easily predicted and are not incorporated into the model.

The results of any in-place enhancements should become readily apparen in the inventories of habitats and in the assessment of the algorithms. For example, if thinnings in pole stands speed the transition to mature timber habitats, this change should be apparent in the inventories; the algorithms for both potential timber index (PTI) and for volume of timber harvested (VT would then be adjusted for the next inventory period.

One important in-place decision for game animals is to schedule annual timber removals within the range of mobility of the animals (U.S. Department of Agriculture, Forest Service 1971). The dispersion of openings can be controlled to some extent by changes in the rates of harvest and sizes of openings, but someone who knows the area's topography must review the specific sites with this principle in mind.

3.8 Adapting DYNAST to Other Types of Forest

The DYNAST-TM program can be modified for use with almost any kind of forest. The following information is required: the delays for succession of habitats; the extent that natural regeneration or artificial reforestatic forms stands similar to those harvested; the ability to predict, at least fo a few decades, the sequential states of community organization; and informa-tion to relate the production of benefits to the states of organization. This kind of information is provided in the literature for many kinds of forests. The most important consideration is to be able to predict the kinc of regeneration that will be achieved after harvest. The problem is more difficult with artificially regenerated stands because of the uncertainty of economic, social, and other factors that determine the commitment of resourc to artificial regeneration.

In the same way that the DYNAST program can be adapted to a specific area, programs can be adapted to different forest types on a single managed area. If one type of forest, i.e., pine, transforms into another type, i.e., hardwoods, the programs for the different types can be linked together to model the transformation. This may be necessary when the types have widely different rates of succession and are interspersed so that algorithms must include habitats of both forest types. However, if the types are spatially separated, i.e., spruce-fir and hardwood types, complexity in both the model and the control constants are reduced by keeping the programs separate.

The illustration presented in this report (chapter 6) is for 6,396 acres of hardwood forest that can be classified into a number of different types. A program could be used for each type and then the programs linked to model conversions, i.e., hardwood stands to white pine or natural transformations among types. This approach may seem to improve the precision of the model, but it might well make the management system less effective. Control would be reduced because the required increase in the variety of decisions and communication channels (Beer 1966) increases the complexity of management actions exponentially. The logical alternative is the one taken in the model.

In this area, the forest types have approximately the same successional rates; the one exception is the yellow-poplar type, but this occupies a small part of the total area. Furthermore, the different forest types have similar value as wildlife habitat. Thus, the variety of management elements and the complexity of management actions can be greatly reduced by treating the forest as one system and merely adjusting the algorithms for timber yields and habitat indices at each inventory. Repeated adjustments keep the model congruent with the real forest and minimize complexity.

3.9 Small Management Areas

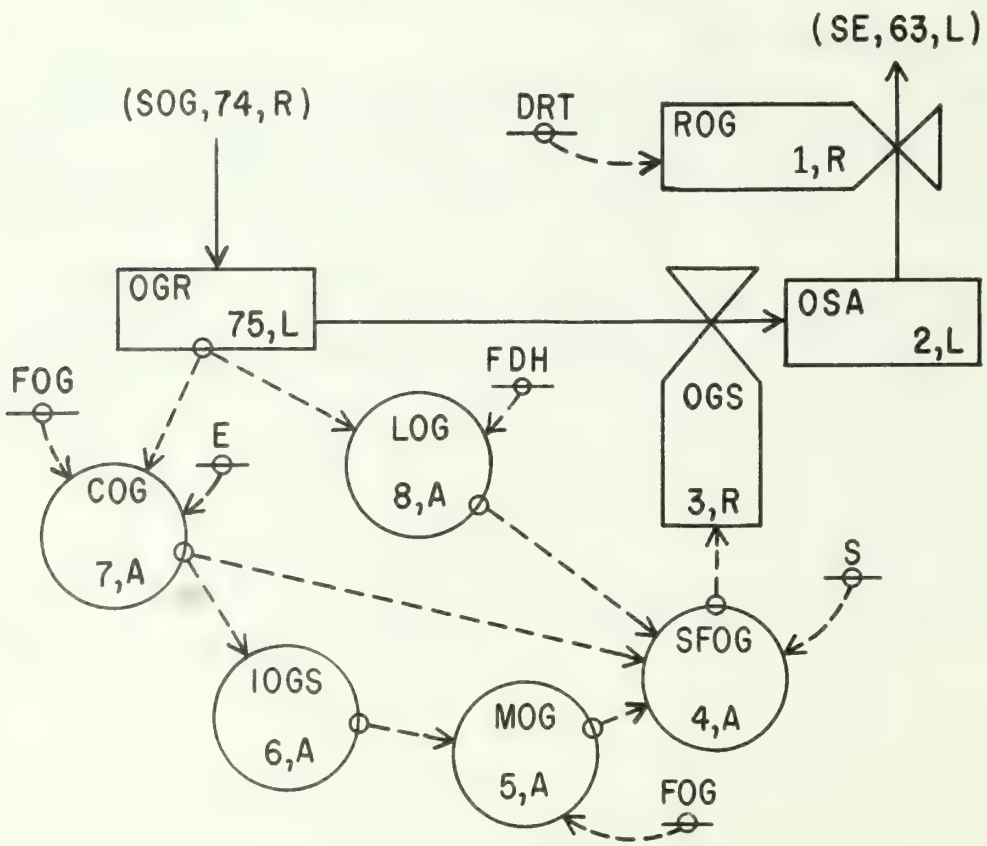
In small ownerships or management areas, it may be impractical to harvest timber every year. If a 40-acre tract is managed on a long rotation, only a fraction of an acre per year is available for harvest. The unit cost of such a small cutting would be high, and the small size of the opening would inhibit regrowth. Thus, the DYNAST-TM system is inapplicable.

A program could be constructed for managing small tracts according to cutting cycles, with intervals of several years between harvests. To maintain good wildlife populations, managers should choose cycles no longer than 5 years. Otherwise there would be no seedling habitat to furnish browse, soft mast, and so on.

4.1 General Information About Equations and Diagrams

Equations for the model are written for the DYNAMO II simulation compiler (Pugh 1976). This compiler is especially useful for revealing the systemic behavior of models with feedback loops and integration equations (Forrester 1961, 1968). The relationship of the equations to the model and the structure of the feedback loops will be illustrated in a series of flow diagrams of the information network (i.e., fig. 9). Arrows indicate the direction of flow. Solid lines indicate changes in the inventory resulting from the harvest of timber and the succession of habitats. Dashed lines indicate a flow of information about the state of the inventory and other parts of the system. Rectangles indicate the amount of area occupied by the different age classes or the amount earmarked for sale and harvest. The areas are computed by level equations identified by "L." Diagrams of "valves" indicate rate equations (R) that describe the changes in the system (succession, sales, and removals) for each interval of computation. To clarify the structure of the model, some of the rate calculations are put in auxiliary equations (A). These equations are diagramed as circles. Straight lines under the abbreviations indicate constants. These are assigned in C-type equations or computed as initial values in N-type equations. The equations are identified in parenthetical references by number and type, e.g., (Eq. 3,R) The equations, with definitions of terms, are listed in appendix A.

Figure 9.--Flow diagram of the information network for the old-growth loop. Each equation is described in the text by number and type.



Each variable has a name and an abbreviation in the DYNAMO notations. The subscript J, K, or L following a decimal point identifies the time of the variable's value. Three successive junctions of computation intervals (DT) are designated for each iteration. K is present. Rates are constant over each computational interval and are subscripted JK for the past interval and KL for the next interval. Variables computed by level and auxiliary equations are subscripted J and K because they have values only for past and present times.

4.2 The Feedback Loops for Timber Removals

The amount of harvest for each year is determined simply by dividing the total area by the rotation age. Once the model forest reaches steady state, the computation of timber removals becomes quite simple. The area of annual harvest will equal the area of the oldest stand and its age will be the selected rotation age. (Certain complexities introduced by practical delays in removal are discussed in section 1.4.3.)

However, during the transition period, the decision process is rather complicated. The model removes the oldest timber first, then moves progressively through the younger habitats. For each year, it scans the oldest category to see whether there is enough timber to fill the harvest quota. If there is not, the model repeats the process for successively younger age classes until the quota is filled (fig. 10). Imbalances in the initial inventory of habitats may cause the future distributions to fluctuate, but the model is able to sense the distribution for each interval, compare it with the desired distribution, and make decisions for harvest that guide the system toward the steady state.

For each habitat, except seedlings, this decision mechanism is described by a series of equations that begins with the equation for removal of timber and proceeds backwards through the feedback loop to the reserves for that habitat. These equations, collectively represented by the circle in the simplified diagram (fig. 4, chapter 2) will here be described in detail.

4.2.1 The Old-Growth Feedback Loop

The amount of old-growth habitat removed (ROG) is determined by the amount of timber accumulated for removal (OSA) divided by the delay in time for removal of timber (DRT) (fig. 9).

(Eq. 1,R, 1.1,C)

The accumulation of old-growth sales (OSA) models a bookkeeping process. The accounting is the integration of old-growth sales (OGS) and the removal of old growth (ROG).

(Eq. 2,L, 2.1,N)

Old-growth sales rate (OGS) is determined by SFOG, which is the total annual sales supplied from the old-growth habitat.

The sale fraction for old growth (SFOG) is a key decision function that is influenced through three paths (fig. 9). At this point, the model decides whether to minimize old-growth sales (MOG loop) or to liquidate old growth (LOG loop). This decision depends on the coverage of old growth (COG) and whether or not there will be old growth at equilibrium, given the

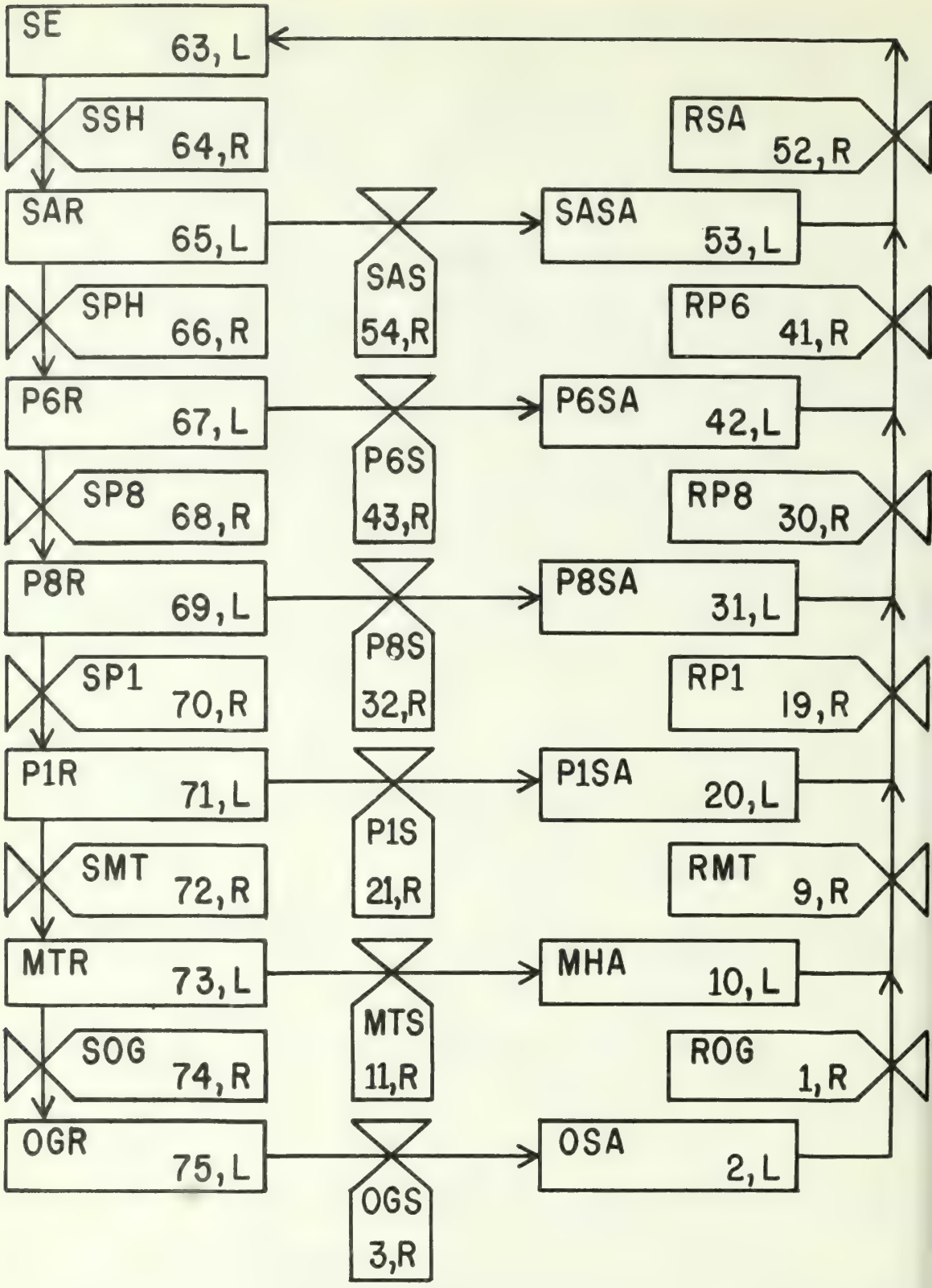


Figure 10.--Flow diagram illustrating the structure of the model for succession, left column, and timber removals, right column. The "valves" indicate rates of succession, left column; rates of sales, center column; and rates of removals, right column. The area of each habitat except seedlings is represented by two rectangles: one for reserves, left column; and one for sales accumulation, right column. Much of the information network is omitted.

chosen rotation age. The function of the MOG loop is to bring the area of old-growth habitat into balance with the amount needed for harvest in the steady state. Often this task requires conserving old-growth stands until the desired distribution of habitats is reached.

The SFOG sector acts to minimize old-growth sales (MOG) unless the area in old growth is three times the area desired at equilibrium. More precisely, the component function FIFGE decides to liquidate old growth (LOG) if old-growth coverage (COG) is equal to or greater than a standard (S), which is a multiple of the old growth needed at equilibrium. In this program, S has the value 3, which is suitable for most situations, but S can be changed at will.

(Eq. 4,A and 4.1,C)

If the computation is routed through the MOG loop, old-growth sales are determined by multiplying the indicated old-growth sales factor (IOGS) and the flow of succession through old growth (FOG).

(Eq. 5,A)

FOG is computed by multiplying the total area being managed (TAH) times the old-growth fraction (OGF), then dividing the product by the period of rotation (ROT) assigned to the run. In the DYNAST-TM program, OGF is a binary function which indicates whether or not there will be old growth in the management area at equilibrium. Its value is 1 if AOG, the age of transition into old growth, does not exceed ROT, the rotation age for the run. Otherwise OGF is 0. If OGF is 0, then FOG will be 0, and there will be no old growth sold through the MOG loop.

(Eq. 5.1,N through 5.7,N)

In a mode with old growth at equilibrium, OGF will be 1 and FOG will be the same as the total annual harvest for the management area (total area divided by rotation age). In this case, the MOG loop proceeds by multiplying the indicated old-growth sales (IOGS) and FOG; the product will be SFOG, the proportion of all sales which comes from old growth.

The factor IOGS is derived from the coverage of old growth (COG) according to a table function (fig. 11). If old-growth reserves are half, or less, of the amount desired at equilibrium, then IOGS is set at zero and no sales occur. As coverage rises from 0.5 toward 1, IOGS causes sales to increase until they equal the total annual harvest for the management area.

(Eq. 6,A and 6.1,T)

Roughly speaking, the coverage of old growth is the ratio of current reserves to the amount needed at equilibrium, but the definition of COG in the model is complicated by switching mechanisms. COG equals current old-growth reserves (OGR) divided by the sum of FOG and E. FOG, the flow of old-growth succession, may equal 0 or the total area of annual harvest. E is a small constant which is added to keep the computer from trying to divide by 0 when FOG has that value.

(Eq. 7,A and 7.1,C)

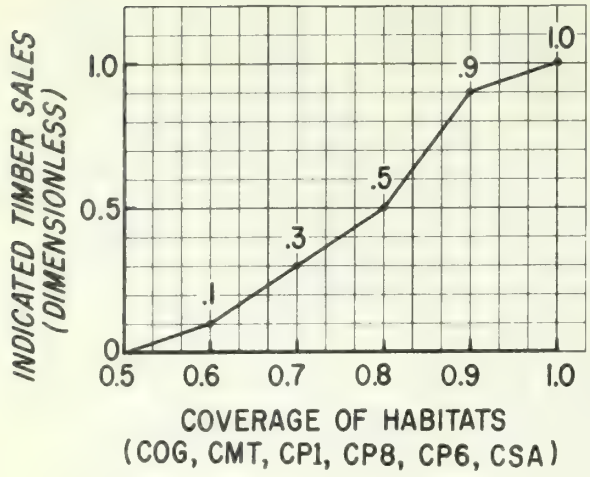


Figure 11.--Table function for indicating timber sales in relation to coverage of habitats.

If coverage (COG) is above 3, the SFOG function switches from MOG to the other loop, LOG, which liquidates old growth. The function of LOG is to simplify the old-growth sector of the model either when a management unit has large areas of old growth in the initial distribution or when the chosen mode of management has a rotation age less than the age of succession into the old-growth class. In the latter situation, when there will be no old growth at equilibrium, the flow of old-growth succession (FOG) equals 0, and, by equation 7,A, coverage (COG) will exceed 3 when there is as little as 0.03 acres in old-growth habitat. Thus, when a low rotation age precludes old growth at equilibrium, the model switches to LOG and liquidates even small stands of old timber. When larger stands are handled through this loop, liquidation is limited to the area of total annual harvest, listed as FDH, "flow of diverted habitats."

(Eq. 8,A and 8.1,A)

When the rotation period is only a few years less than the transition age for old growth (AOG), a small fraction of the stands continues to succeed into the old-growth habitat. These stands are removed through the LOG portion of the old-growth loop because the value for FOG will be 0 and the coverage (COG) will be equal to or greater than 3 any time there is more than 0.03 acre of old-growth reserves (OGR).

4.2.2 The Mature Timber Feedback Loop

The amount of mature timber removed (RMT) is determined by the decision to harvest and the delay for removal (fig. 12). The amount of timber accumulated for removal (MHA) divided by the delay in removal of timber (DRT) estimates the amount removed for each interval of time.

(Eq. 9,R)

The accumulation of mature timber sales (MHA) models a bookkeeping process. The accounting is the integration of mature timber sales (MTS) and removal of mature timber (RMT).

(Eq. 10,L through 11,R)

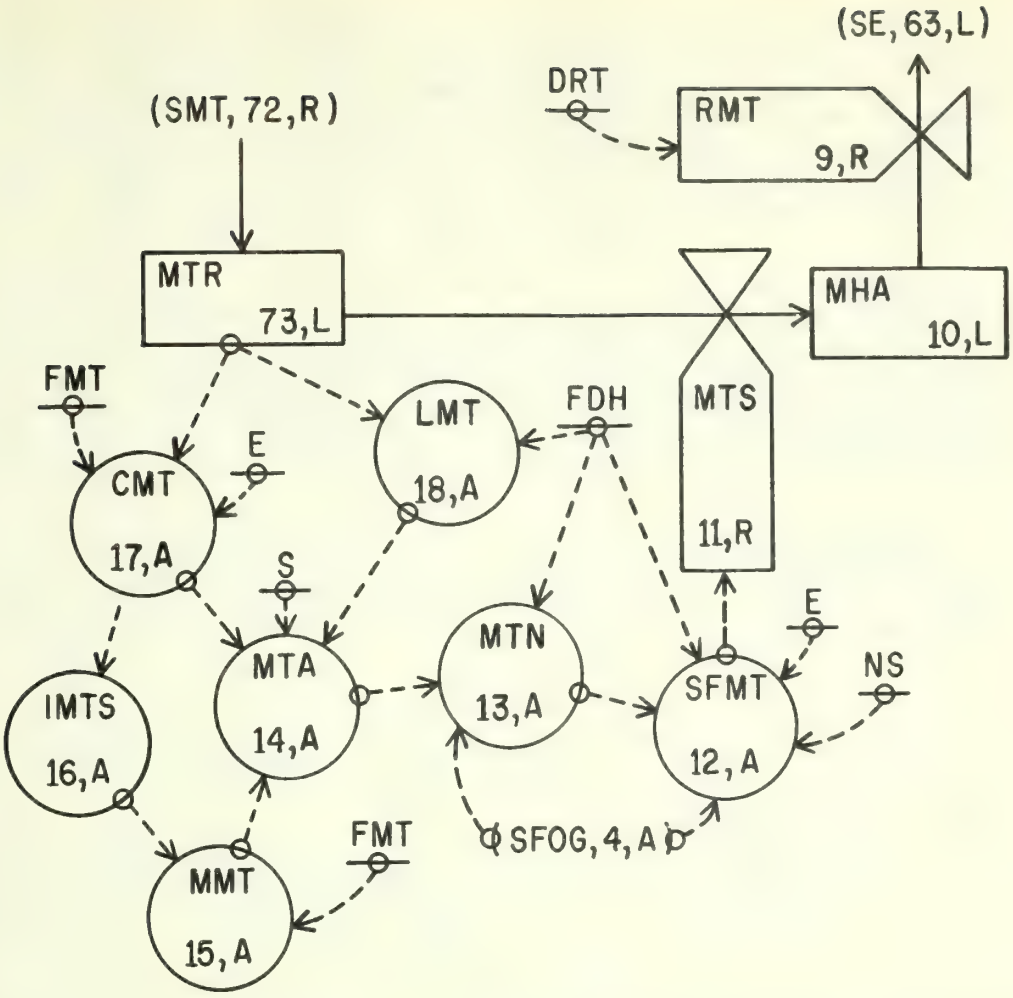


Figure 12.--Flow diagram of the information network for the mature timber loop. Each equation is described in the text by number and type.

The rate of mature timber sales (MTS) is the sale fraction of mature timber (SFMT), the proportion of all sales which comes from mature timber habitats. This sale fraction is determined by a series of decision mechanisms that relate the sale of mature timber to the amount of old growth being sold, to any deficit in total sales for the area, and to the availability of mature timber. By function FIFGE, no mature timber will be sold if the sale of old growth (SFOG) fulfills the quota for annual harvest (FDH) for the selected rotation. The constant E is used in this equation to avoid trifling sales of mature timber when the sale fraction of old growth is within 0.01 of FDH. When SFOG is less than FDH, the sale of mature timber (SFMT) is determined by the amount of mature timber needed (MTN).

(Eq. 12,A)

The amount of mature timber needed (MTN) is that part of the deficit left after old-growth sales which can be made up from available mature timber. The computer selects whichever is smaller, the old-growth deficit (FDH minus SFOG) or the amount of mature timber available (MTA).

(Eq. 13,A)

The MTA sector is a decision point parallel to the one in the old-growth loop. Mature timber available (MTA) may be computed through either one of two paths, LMT (liquidate mature timber) or MMT (minimize mature timber sales). The function FIFGE minimizes mature timber sales (MMT) unless the coverage of mature timber (CMT) is greater than or equal to the constant S, here assigned the value of 3. If the coverage equals or exceeds 3, sales proceed through the LMT path up to the annual limit (FDH).

(Eq. 14,A)

As in the old-growth sector, the model will use the MMT path to minimize sales and build the reserves needed for equilibrium when the rotation period is in the age class for mature timber. In MMT, the rate of sales is the product of the indicated mature timber sales (IMTS) and the flow of mature timber habitat (FMT). The flow of mature timber is the total area of habitats (TAH) times the mature timber fraction (MTF) divided by the rotation period (ROT).

Again, MTF is a binary indicator of whether or not there will be mature timber at equilibrium. If MTF is 0, FMT becomes 0 and the minimum sales pathway is switched off. If MTF is 1, FMT equals total annual sales (FDH).

(Eq. 15,A through 15.4,N)

Because, when MMT is functioning, FMT equals total annual sales, the product of IMTS and FMT yields the fraction of all sales coming from mature timber habitats.

Indicated mature timber sales (IMTS) are scaled according to coverage (CMT) by the same table function as used for the old-growth habitat (fig. 11).

(Eq. 16,A)

The coverage of mature timber (CMT) is the area in mature timber reserves (MTR) divided by the sum of FMT (flow of mature timber habitat) and the constant E. The constant E prevents attempted divisions by 0 and is important in the choice between the liquidating (LMT) and minimizing (MMT) pathways for computing sales.

(Eq. 17,A)

If the decision is made to liquidate mature timber reserves (LMT), the rate of sales equals the total annual harvest (FDH) or the amount of mature timber reserves (MTR), whichever is the smaller.

(Eq. 18,A)

4.2.3 Pole and Sapling Feedback Loops

The feedback loops for the pole and sapling habitats are similar to the mature timber loop. This section will describe only the differences. The flow diagrams and the equations may be used to compare the loops.

Each of the pole and sapling loops has an equation that accumulates the sale fractions for all older habitats. For the 10-inch pole loop (fig. 13) this (SOM) is the sum of the sale fraction for old growth (SFOG) and the sale fraction for mature timber (SFMT). SOM is used in the decision process in the same way that SFOG is used in the mature timber loops.

(Eq. 19,R through 29,A)

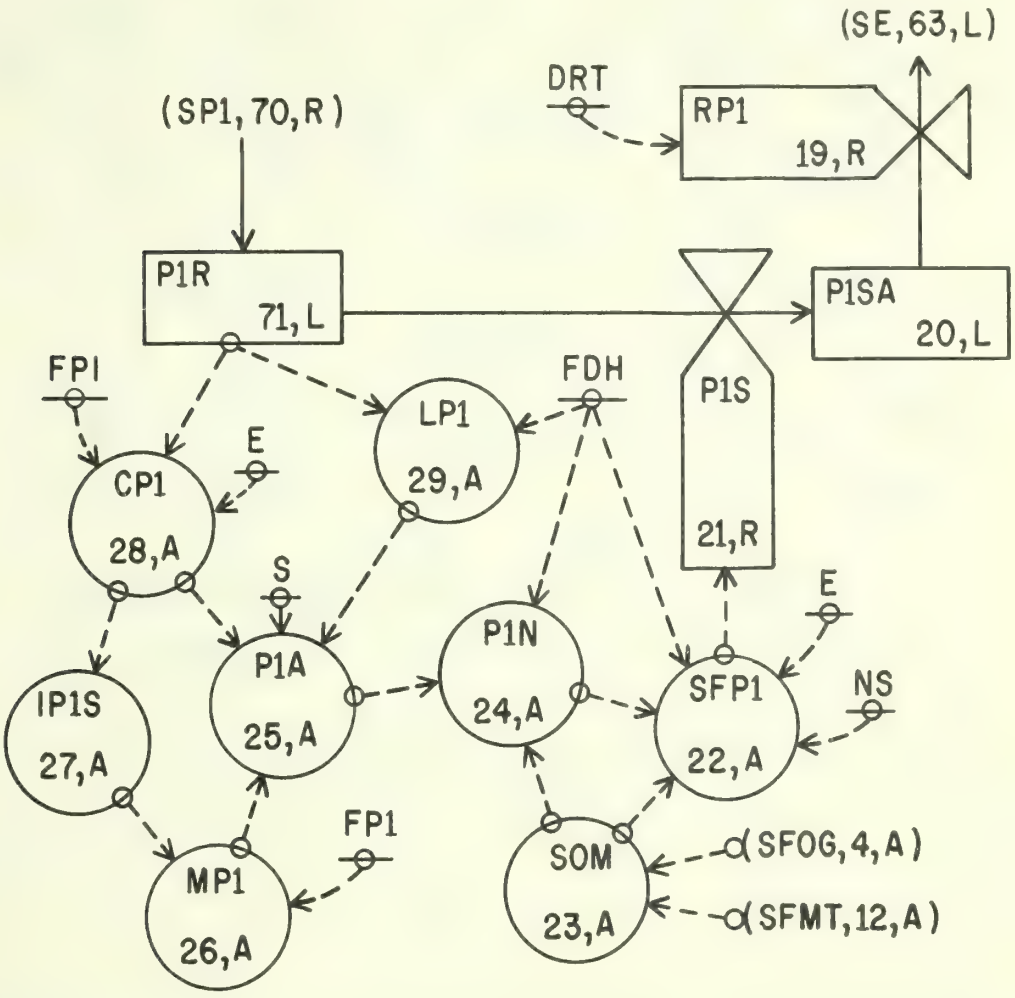


Figure 13.--Flow diagram of the information network for the 10-inch pole timber loop. Each equation is described in the text by number and type.

For the 8-inch loop the sale fraction for 10-inch poles (SFP1) is added to SOM to accumulate the sales (SOM1) for older habitats (fig. 14).

(Eq. 30,R through 40,A)

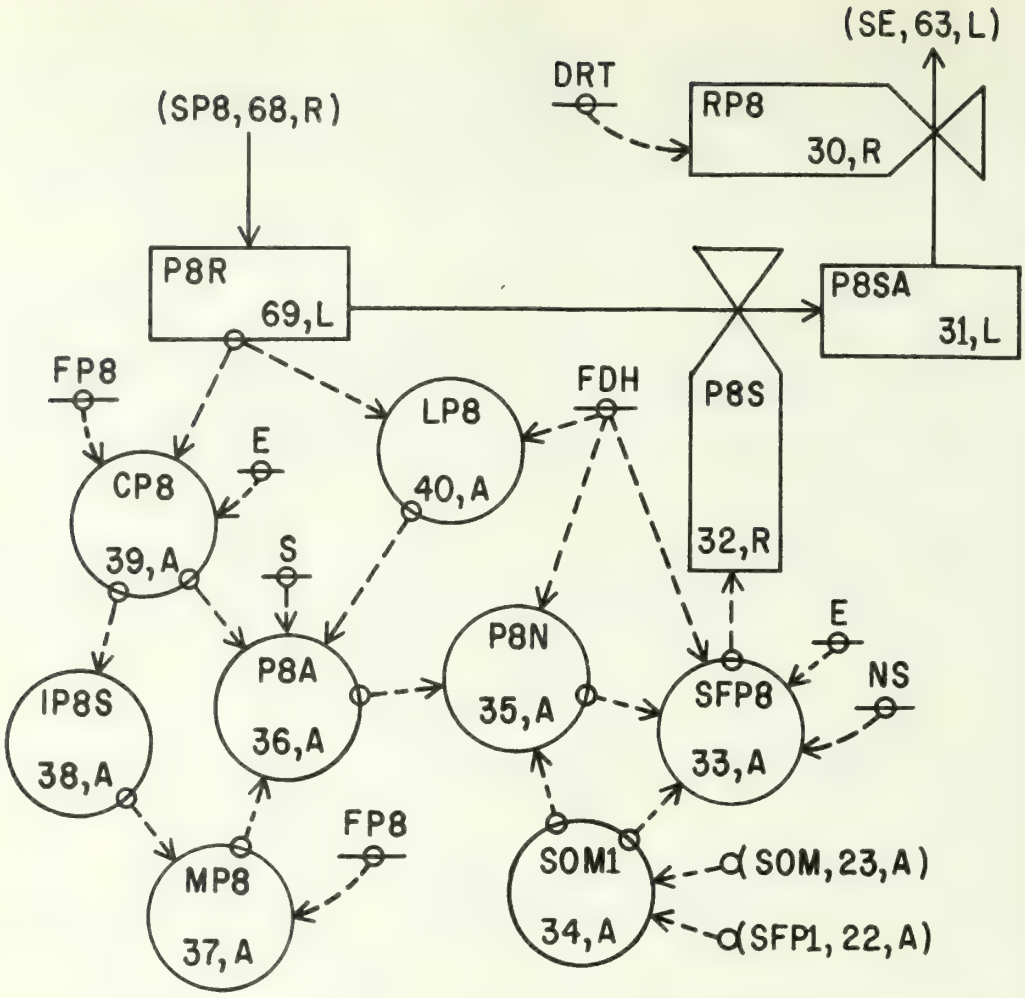


Figure 14.--Flow diagram of the 8-inch pole timber loop. Each equation is described in the text by number and type.

For the 6-inch pole loop the sale fraction for the 8-inch poles (SFP8) is added to SOM1 to accumulate sales (SOM8) for the older habitats (fig. 15).

(Eq. 41,R through 51,A)

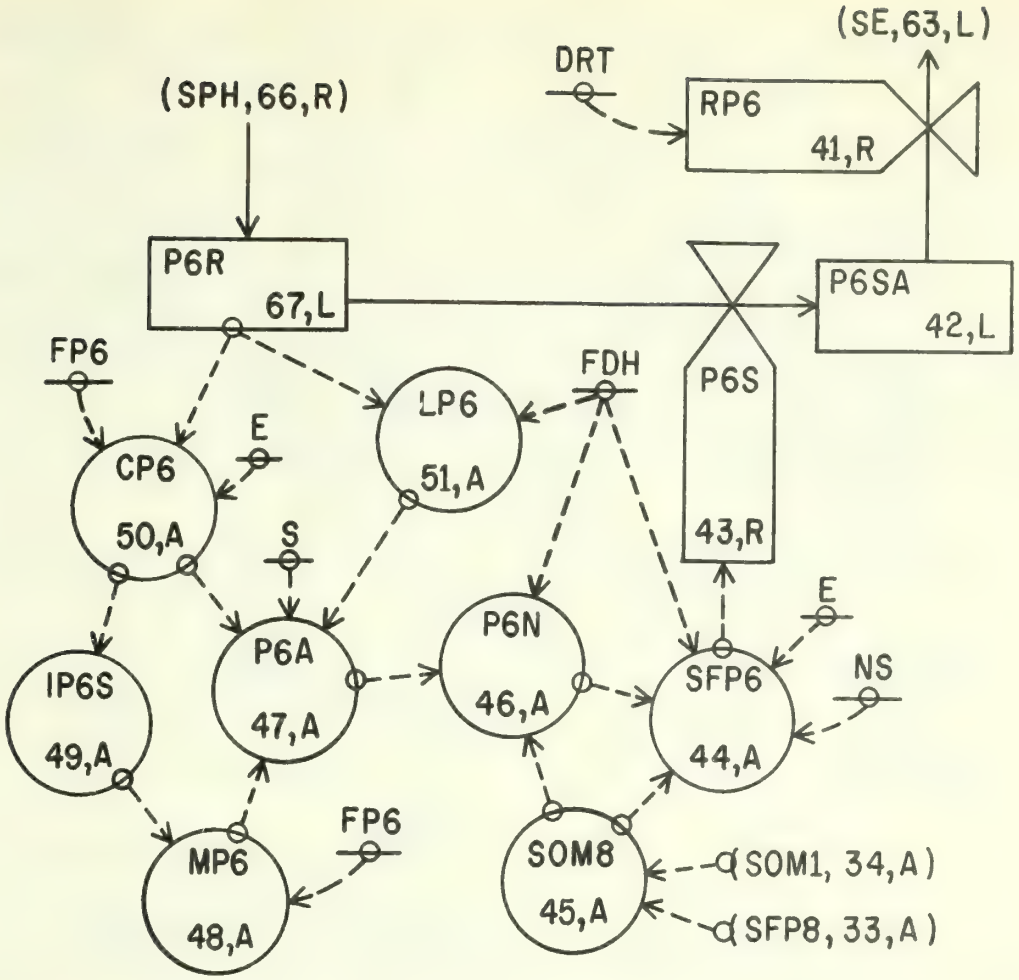


Figure 15.--Flow diagram of the 6-inch pole timber loop. Each equation is described in the text by number and type.

For the sapling loop the sale fraction for the 6-inch poles (SFP6) is added to SOM8 to accumulate sales (SOM6) for the older habitats (fig. 16).

(Eq. 52,R through 62,A)

During the transition period, these accumulating mechanisms allow the model to trace the complex patterns of harvest that develop from different initial distributions. Once the steady state is reached, all sales come from the oldest habitat types.

4.2.4 The Transformation of States of Succession

Once an area is diverted to seedling habitat, mortality of seed, seedlings, and sprouts organizes the survivors into succeeding classes of habitats. The delays for successional change are estimated from historic data. For the Appalachian example, the process and the derivation of delays are described in section 3.3.

(Eq. 63,L through 75.1,N)

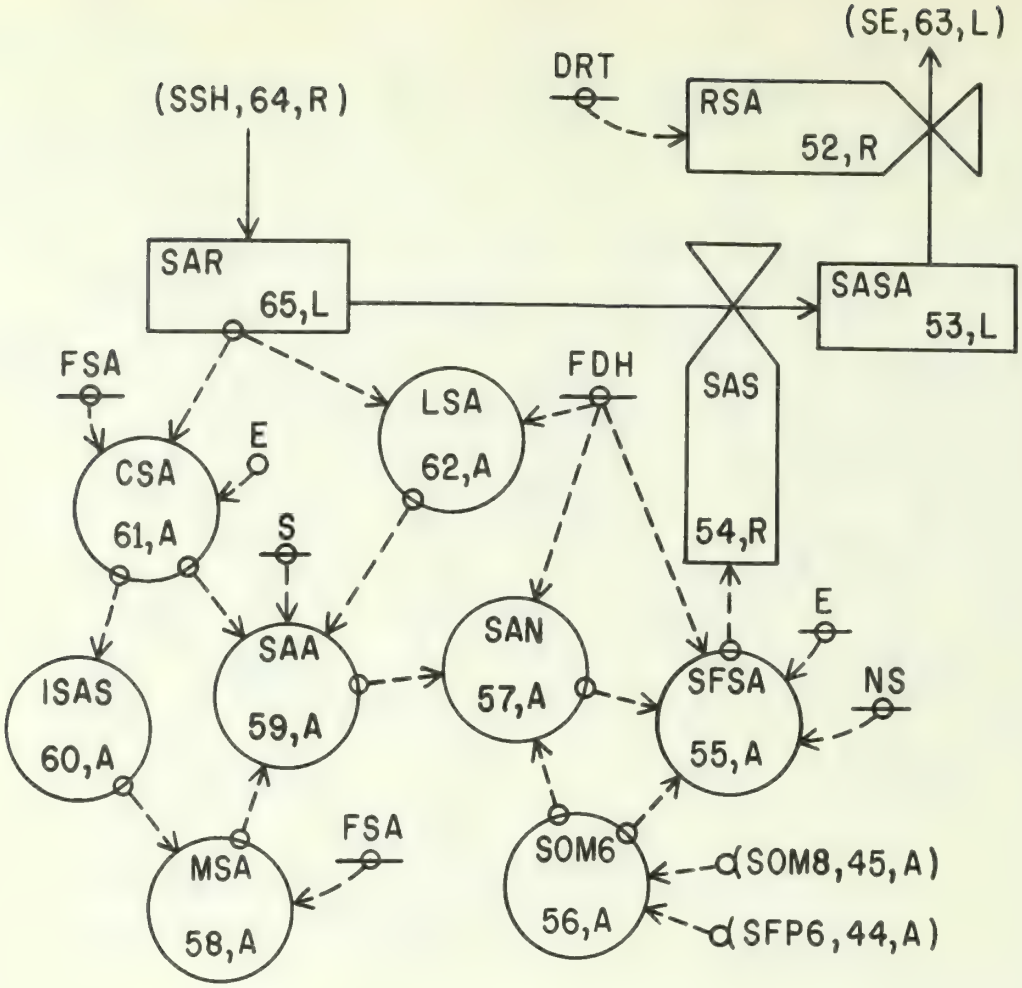


Figure 16.--Flow diagram of the sapling loop. Each equation is described in the text by number and type.

4.3 Supplementary Information

Supplementary equations are used to derive information about the dynamics of the model. A large number of characteristics about the modeled forest can be computed with supplementary equations.

(Eq. 76,S through 92,S)

4.4 Regulation of the Size of Openings

Only one opening size (SO) and one standard deviation of opening (SDO) are required for DYNAST-TM. This makes the calculation of opening-size distribution (OPS), number of openings (NOP), and number of openings per square mile (OPM) considerably simpler than for DYNAST-MB, which may use different opening sizes for old growth and mature timber.

(Eq. 93,S through 96,S)

5. A TECHNICAL REPORT ON SAMPLE ALGORITHMS FOR EASTERN HARDWOOD FORESTS

The algorithms are statements of relationship between the distribution of habitats in the forest and the benefits available from the forest. They are written as supplementary equations by which the model projects an estimate of benefits. Constructing and validating algorithms is part of the continuing application of the DYNAST-MB system (sec. 3.4).

Seventeen algorithms for eastern hardwood forests have been constructed for the current version of DYNAST-TM. While they are ready for use, and indeed have been used to screen modes of management for a pilot application of the model, they are best regarded as tentatively formulated examples. New algorithms can be formulated for other benefits, and the extant ones will need to be adjusted by experience and research.

The following sections describe the 18 algorithms and give sources for information used to construct them. In some cases, the listed sources are only examples selected from an abundance of published research.

The benefit and impact equations are essentially the same as for DYNAST-MB (Boyce 1977). Thus, the plots and the printed tables can be directly compared. The minor differences in the DYNAST-TM equations are due to the use of only one size of opening (see for an example equation 93,S for SO) and the use of only one rotation period (ROT) which may vary from 6 to 320 years.

5.1 The Potential Timber Index (PTI)

The potential timber index is a ratio of the volume of timber harvested under a given mode of management and the volume of timber that would be expected if timber production were favored over all other benefits. This ratio is important for selecting the mode of management that will provide the amounts and kinds of timber required for a forest business. The computation of the ratio changes as the distribution of habitats found in the initial inventory is changed to the distribution required for the selected rotation period. The description of the equation begins with the modification of the timber volume index ratio (TVI) to reduce the potential timber index (PTI) by a size of opening factor (SOF) when the openings are less than 3 acres.

(Eq. 97,S)

The data for the timber volume index (TVI) come from Schnur (1937), modified by information from Beck and Della-Bianca (1970), Dale (1972), and unpublished data from Frothingham (see footnote 1), and the Forest Survey.

The mean annual increment of cubic volume for stands of mixed Appalachian hardwoods peaks at about 50 years of age (Schnur 1937). Yellow-poplar stands, less than 13 percent of the forest (Boyce and McClure 1975), may peak a few years earlier (Beck and Della-Bianca 1970). The age of 50 is used as the reference age to develop a timber yield index (TYI). The index assumes that 100 percent stocking and an average site index of 70 (Knight 1978) will be typical. Under these conditions it computes expected yields for a mode of management and compares them with the yield at age 50. Of course, other ages for maximum production of timber could be used as the reference age.

At 50 years of age the timber yield index (TYI) is 1.00 (table 3). As age increases, both the yield and the timber yield index increase, but at a decreasing rate. We do not have enough information to predict increments accurately beyond 110 years. From Frothingham's reports of measurements of recently felled virgin stands in 1915 (see footnote 1), it appears that yield in cubic volume may exceed 10,000 cubic feet per acre for a few stands at about 300 years of age. Frothingham reported that most stands held more than 6,000 cubic feet per acre. Extending the yield to 5,600 cubic feet per acre at 320 years is probably conservative. The timber yield for different age classes is entered as a table function (fig. 17).

The timber-maximum rotation age (TMR) is the age selected for harvest if timber is preferred over all other benefits. For this example, maximum production of cubic volume to a 4-inch top is 50 years (Schnur 1937). Other ages would be used for other forest types and other kinds of timber products such as saw logs to a 9-inch top in the Appalachians (Boyce 1977).

Table 3.--The periodic annual increment, mean annual increment, yield, and timber yield index for selected ages of hardwood forests in the Appalachians[1/]

Age	Periodic annual increment	Mean annual increment	Yield[2/]	Timber yield index (volume units/acre)[3/]
Years	- - - - - Cubic feet per acre - - - - -			
20	48	53	1,090	0.41
50	51	53	2,680	1
80	42	49	3,950	1.47
110	34	45	4,960	1.85
140	8	37	5,200	1.94
170	4	31	5,320	1.98
200	2	27	5,380	2.01
230	2	24	5,440	2.03
260	2	21	5,500	2.05
290	2	19	5,560	2.07
320	1	17	5,600	2.09

1/ Based on table 34 for site index 70 (Schnur 1937) and extended to older ages from unpublished data (see footnote 1, page 21).
2/ Volume inside bark for all trees 0.6 inch d.b.h. and larger.
3/ Yield (cubic feet per acre) divided by 2,680.

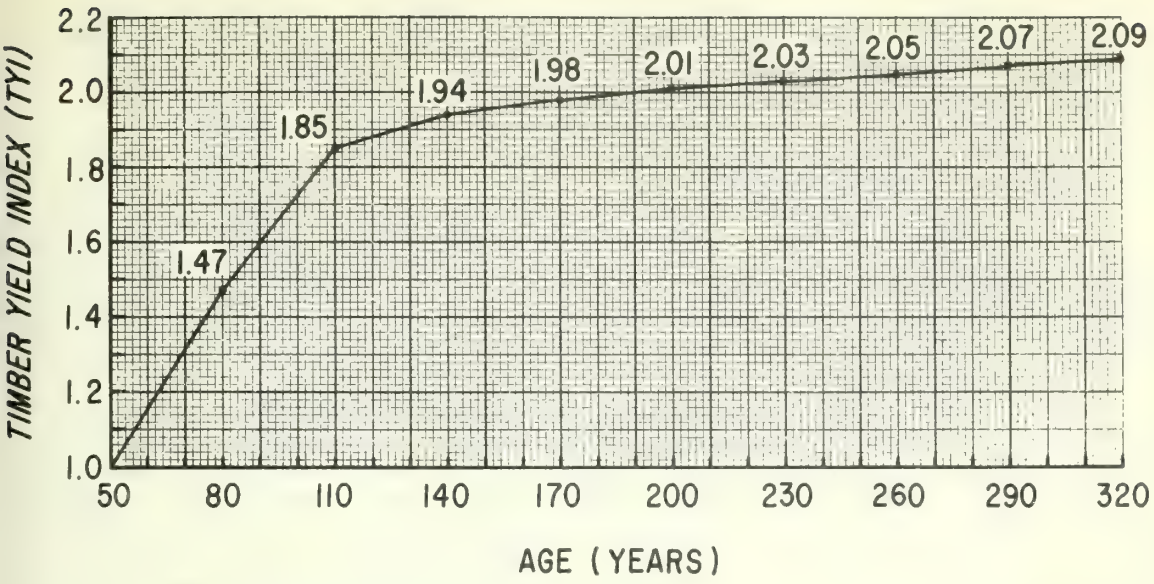


Figure 17.--Timber yield index (TYI) versus age of forest stands (years) (Eq. 98; see table 3).

The timber index maximum (TIM) is an index of the amount of timber expected per year for the timber-maximum rotation age (TMR). It is the total area of habitats (TAH) divided by the timber-maximum rotation age (TMR); then this area is multiplied by the timber yield index (TYI).

(Eq. 98,S through 98.4,C)

Annual volumes of timber removed are computed for each habitat. The equations are essentially the same for each habitat, so computations will be described only for the old-growth habitat. The timber volume of old growth removed (TVO) is the area of old growth harvested (ROG) multiplied by the volume per unit area (OGVF). The volume per unit area, measured as volume units (table 3), is taken from the table function for timber yield (fig. 17) according to age of harvest. The harvest ages for each of the fractions are dynamically corrected for volume per acre by estimating the ages of the stands at the time of harvest. The minimum age for old growth is known from AOG, the average age for stands entering the old-growth habitat. Each year an amount of area (FOG) enters the old-growth habitat. The age at harvest can be estimated by adding to the minimum age (AOG) the number of FOG's that have accumulated. Thus, the harvest age of old-growth timber (HAOG) is the amount of old growth accumulated (OG) divided by the annual additions (FOG) and added to the minimum age (AOG) less one year, the transition period. The harvest age for the other habitats is computed in a similar way.

(Eq. 99,S through 116,S)

Because small openings reduce the growth rate for young trees and increase damage to surrounding trees during harvesting, the potential timber index (PTI) is reduced whenever the average diameter of openings is less than 3 acres. Harvest of timber from small openings injures the crowns, roots, and trunks of surrounding trees. The losses may not be apparent at the time of harvest, but in time the total yield is reduced (Biltonen and others 1976; Nyland and others 1976).

It is difficult to remove a large tree without creating an opening of at least 0.2 to 0.6 of an acre. The natural felling of trees in old-growth stands forms openings of this size (Williamson 1975). About 0.2 of an acre is the smallest size of opening for the felling, bucking, and removal of a large tree.

Growth in small openings is slow for seedlings, sprouts, and residual trees (Roach and Gingrich 1968; Trimble 1970, 1973; Marks 1974). Growth is also retarded near the border of an opening of any size. As the size of the clearing decreases, the ratio of internal area to perimeter decreases. In a 3-acre, circular opening, there are 100 square feet of area for each running foot of perimeter. In a half-acre opening, the area per perimeter foot is only 40 (fig. 18). The limitation on growing space caused by this border effect is probably insignificant for openings larger than 3 acres, but it rapidly becomes more severe for smaller openings. In the timber algorithm, the small opening factor (SOF) adjusts for losses on a curve which approximates the relative increase in perimeter when area declines (fig. 19).

(Eq. 58, 59)

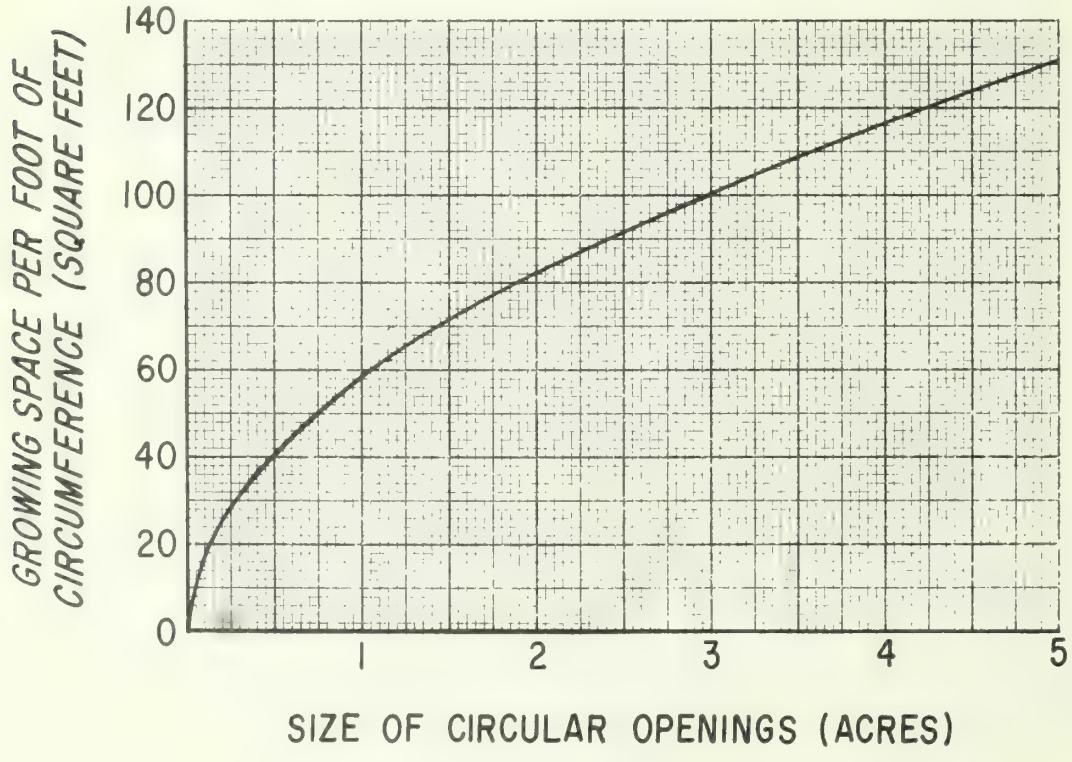


Figure 18.--The "border effect" in relation to the size of circular openings as indicated by the growing space per foot of circumference.

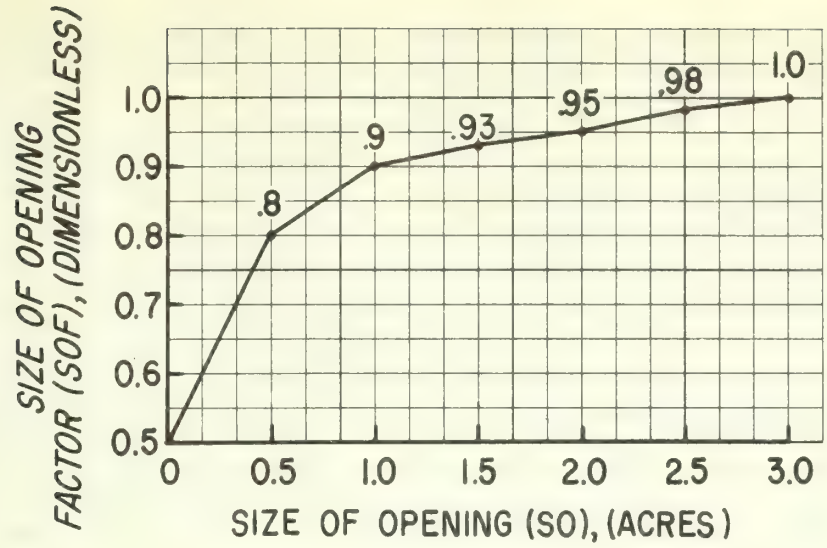


Figure 19.--Size of opening factor versus size of opening.

5.2 Volume of Timber Harvested (VT)

The timber yield index used here (TYI, fig. 17) is a compromise. In the real forest, different site classes and densities of stocking affect the relationship between age and volume (Schnur 1937, table 34). Recently Carmean (1971) and others have presented evidence for improving predictions of growth by using polymorphic curves for separate species by site classes. In the DYNAST system, this amount of detail is not considered important for management decisions, since the primary concern is to consider the dynamics of the forest and to compare the relative yields of the modes of management, rather than to make specific predictions as one would in preparing for a sale. An enormous variety is generated by the mixture of different site index classes and species in an area; moreover, we can only approximate the yields of specific areas to be harvested in the future. Thus, it is necessary to use averaged values. Actually, the variance of site index from the average is relatively small for eastern hardwood forests (Schnur 1937; Knight 1978). For a specific management unit, the model can be started with the yield values listed in table 3. After several decades of inventories and timber sales, the figures in table 3 can be adjusted to predict yields more accurately.

This timber yield index (TYI) or one modified for a specific area can be used to approximate the volume of timber expected to be harvested with different modes of management. This is done separately for removals from each habitat. The old-growth habitat is again used as an example. Remembering that TVO (Eq. 99,S) is the number of volume units of mature timber harvested at a given time, we have only to multiply the number of TVO units by the volume of a unit to estimate the volume of old growth removed (VOG, Eq. 161,S). This volume is corrected for losses due to small openings (SOF).

The size of one volume unit at age 50 is found in the yield table (table 3) to be 2,680 cubic feet/acre, inside bark for all trees 0.6 inch d.b.h. and larger, stump to tip. The model runs presented in this report use a definition for merchantable volume units. In this definition (Y50, Eq. 166.1,C) the value of a volume unit is reduced to 2,520 cubic feet/acre as an estimate of volume inside bark, stump to a 4-inch top, for trees 4 inches and larger at d.b.h. Since the timber yield relationship is one of a family of harmonized curves, other values can be used for the constant Y50.

The total volume of timber harvested (VT) is the sum of the volumes c timber harvested from all habitats.

(Eq. 160,S through 166,S)

5.3 Sediment Flow Index (SEMT)

The sediment index is described fully in section 2.2.3.

(Eq. 118,S and 118.1,T)

5.4 Ugliness Index (UGL)

The ugliness index reflects the disorderly appearance of recently harvested areas. The components of the index are the proportion of total area in seedling habitat (PSE), the number of openings per square mile (OPM and the opening-size distribution (OPS).

(Eq. 124,S through 127.1,S)

The index increases as any of these increase. For seedling habitat, the unacceptable limit for ugliness is 6 percent of the total area (fig. 20 For the number of openings, the limit is one per square mile per year (fig. 21). For size of openings, the limit is 30 acres (fig. 22). This index is further described in section 2.2.4.

5.5 Visual Variety Index (VIS)

This index measures visual contrast in forest landscapes, on the assumption that variety contributes to esthetic appeal (see sec. 2.2.4). Among elements that can be controlled, the contrast in height of timber stands is the main variable. Three height classes are used to compute the index: old growth, other stands over 50 feet, and stands under 50 feet (figs. 23, 24, and 25). The index rises to 1 when the three classes are in balance, with each occupying 30 to 40 percent of the area.

A 30 percent proportion of old growth is optimal for the visual appea index. Beyond that, there is less room available for contrasting younger stands, and the index declines. The contribution to the index by the other two classes is highest when they are in exact balance.

The proportion of area in seedlings is important because the diversic of mature stands to seedling habitat regulates visual contrast in the older stands. Seedling stands also add contrast. However, the proportion of the total area in seedling habitat will rarely exceed 7 percent, and not more than 4 percent is needed to maintain a balanced distribution of older stand The visual index can be 1 when seedling habitat equals 4 percent of the tot area. As the proportion of seedling habitat increases or declines, an imbalance in contrast will begin to appear in the older stands as time progresses.

(Eq. 119,S through 123.1,T)

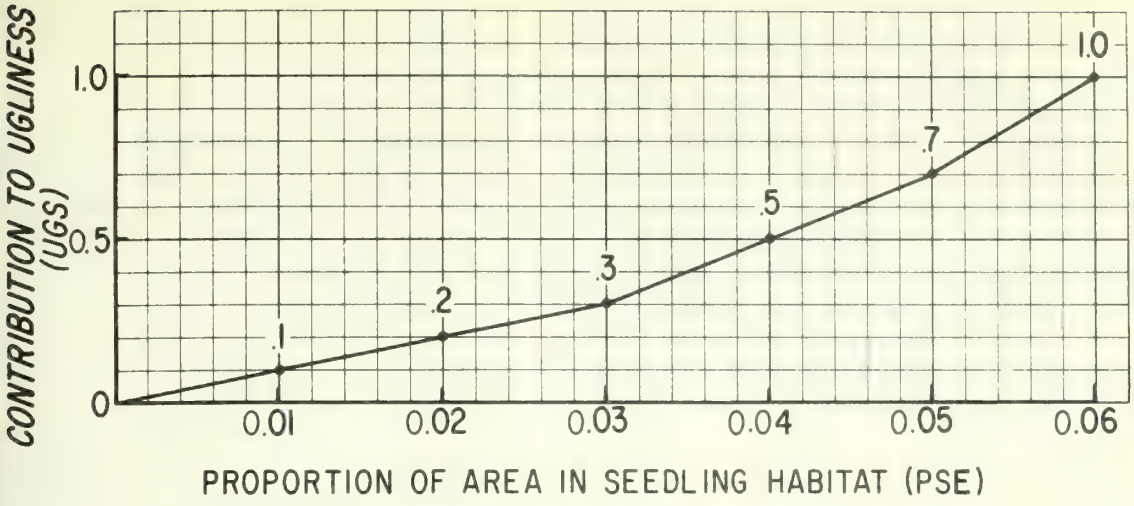


Figure 20.--Contribution to ugliness by the proportion of total area in seedling habitat.

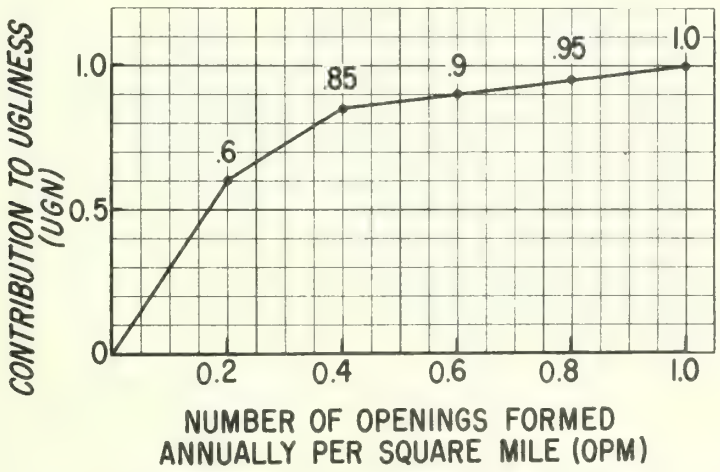


Figure 21.--Contribution to ugliness by the number of openings formed annually.

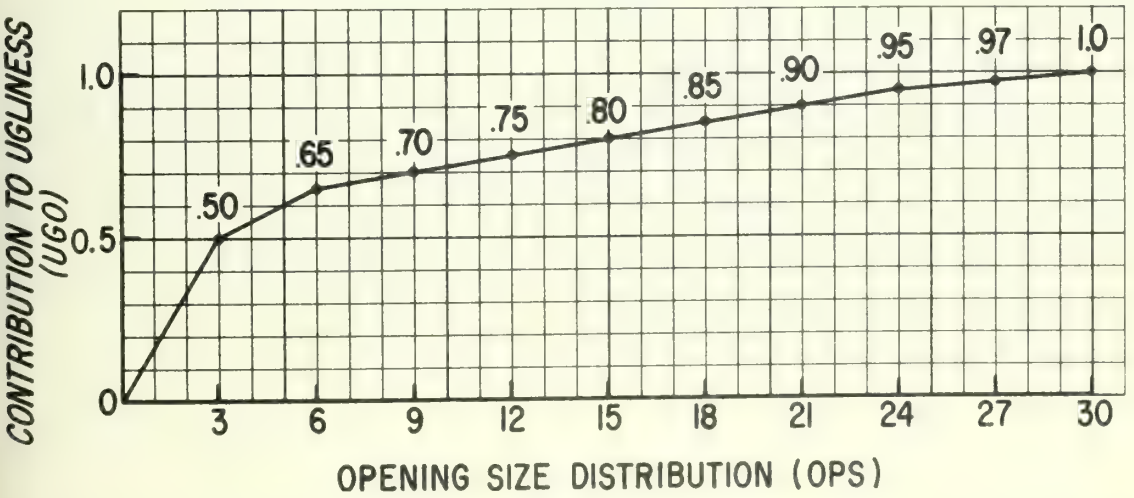


Figure 22.--Contribution to ugliness by the distribution of size and openings (OPS) (acres).

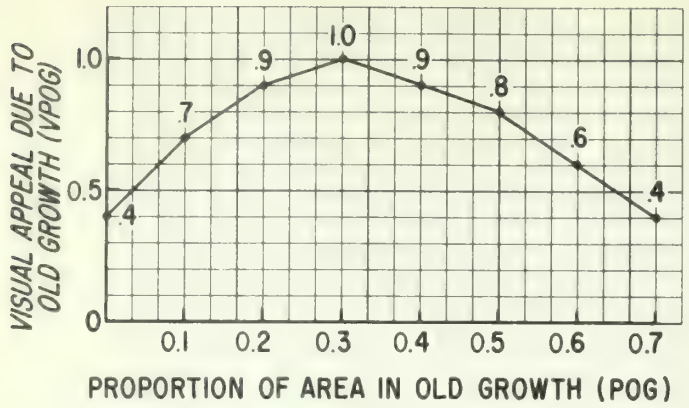


Figure 23.--Visual appeal due to the prop
tion of total area in old-growth habita

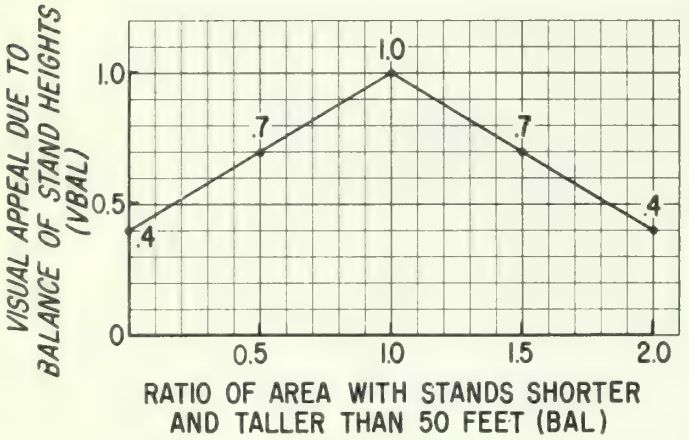


Figure 24.--Visual appeal due to the bala
of stands shorter and taller than 50 fee

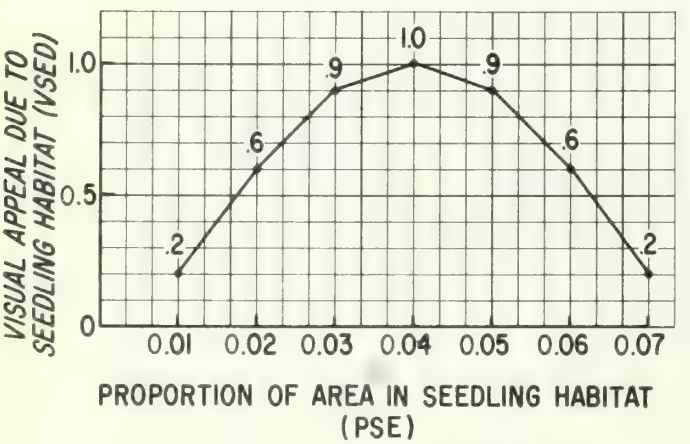


Figure 25.--Visual appeal due to the prop
tion of area in seedling habitat.

5.6 Deer Habitat Index (DEER)

The adaptable whitetail eats many foods, including forage, acorns, nuts, fleshy fruits, and fungi. Hard mast, needed for winter food, and browse are the most important parts of the diet. Thus, mast-producing stands and seedling habitats contribute to the deer index.

Seedling habitat contributes an increasing amount of forage and soft mast as the proportion of area (PSE) increases to 7 percent. Larger proportions are assumed to make little or no additional contribution to the availability of forage (fig. 26).

Deer can use the forage most effectively when it is dispersed in a number of small openings. Figure 27 shows how the contribution to the deer index rises as openings decrease to 6 acres. The contribution of opening type for deer (OTD) multiplied by the deer habitat index (HTD) reflects the way that the pattern of openings affects the availability of browse.

The amount of hard mast is related to the proportion of area in 10-inch pole and mature timber habitat (fig. 28). Mast production is assumed to be adequate when 20 percent or more of the area is in mast-producing habitats. Species composition cannot easily be predicted (McGee 1975; Trimble 1970, 1973; Sander and Clark 1971; McGee and Clark 1975); however, it is assumed that mast-producing species will be present and that the proportion of area in mast-producing age classes is a serviceable index to mast production.

(Eq. 132,S through 135.1,T)

5.7 Squirrel Habitat Index (SQU)

Squirrels of all kinds are almost wholly dependent upon escape dens and forests that produce hard mast. Heavy production of hard mast requires large numbers of nut- and acorn-producing trees between 50 and 130 years of age and with diameters from 8 to 20 inches. The proportion of the areas in 8- and 10-inch pole timber and mature timber habitats is the most important component of the squirrel habitat index.

The second component of this index is the availability of dens for escape and nesting (U. S. Department of Agriculture, Forest Service 1971). Dens are present in mature timber stands but are more frequent in the old-growth habitat. Although old growth typically has a lower production of mast than mature and younger habitat, some old growth, if well distributed, improves squirrel habitat.

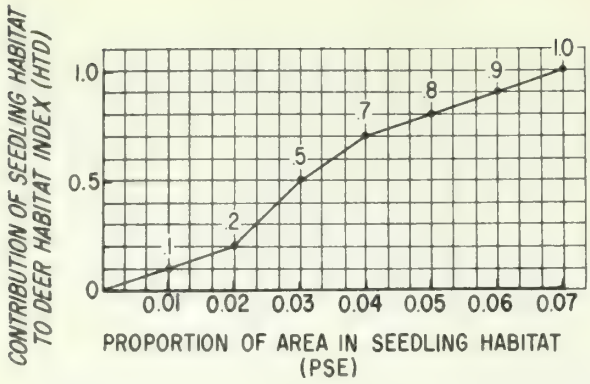


Figure 26.--The contribution of the portion of area in seedling habita the deer habitat index.

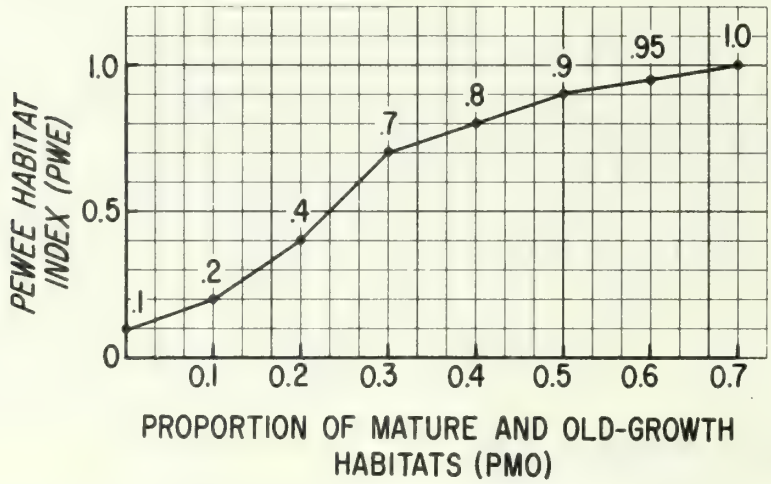


Figure 27.--The contribution of opening-size distribution (OPS) to deer habitat.

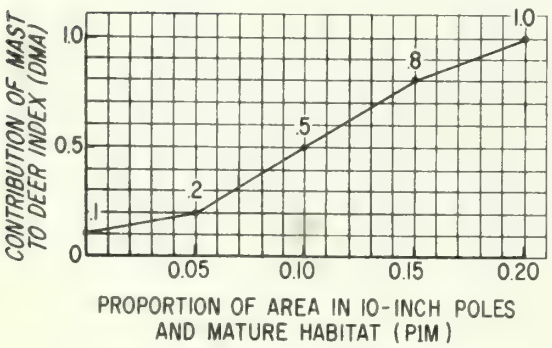


Figure 28.--Contribution of mast to habitat index versus the proportio 10-inch poles and mature timber.

The type-habitat index for squirrels (THS) increases as the proportion of area in 8-inch and 10-inch poles and mature timber (P08M) increases (fig. 29). Only about 40 percent of an area can be maintained in these age classes for long periods, so this proportion is assumed to be the practical limit for the index.

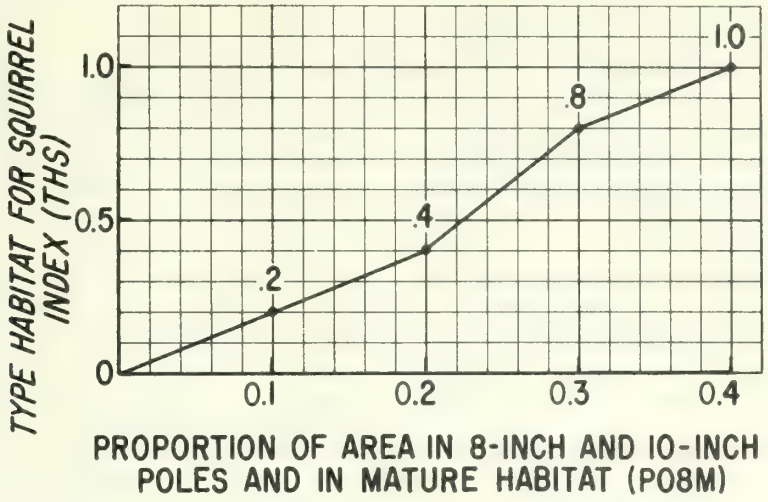


Figure 29.--Type of habitat for squirrel index versus the proportion of area in 8-inch and 10-inch poles and mature habitat.

A relatively small proportion of old-growth habitat, if well distributed through the management unit, can supply nest and den cavities. The index for dens (SDT) increases rapidly as the proportion of old growth increases from 0 to 30 percent of the total area (fig. 30). As the proportion of old-growth habitat increases, however, the proportion of stands in 8- to 10-inch pole timber and mature timber declines and the overall index declines. In this way the index reflects the relative distribution of stands for mast production and for cavities.

(Eq. 136,S through 138.1,T)

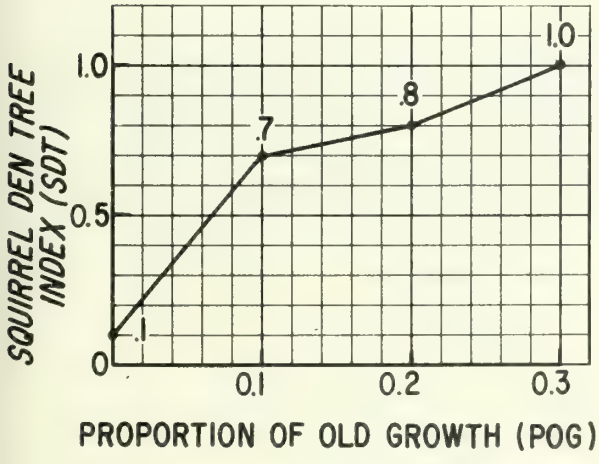


Figure 30.--Squirrel den tree index versus the proportion of area in old-growth habitat.

5.8 Turkey Habitat Index (TUR)

A primary winter food of turkeys is hard mast. During the warm months openings produce much of the insects, soft mast, and other foods needed. Openings also serve as breeding, nesting, and brooding areas. These are the two important components of this index.

(Eq. 139,S through 141.1,T)

The index for turkey-type habitat (TURT) increases as the proportion of area in mast-producing trees (P08M) increases (fig. 7, sec. 3.4). The limit is assumed to be when 50 percent of the area is in 8- and 10-inch poles and mature timber.

The ideal size of openings for turkeys is not known. The amount of marginal area is probably more important than the amount of total area in seedling habitats. Feeding, nesting, and often roosting seem to be associated with the transition area across the margin of openings. The algorithm assumes that turkeys benefit when harvest patterns create a maximum amount of usable margin for a given rate of timber harvest. According to the literature (Halls 1975), turkeys apparently use the margins of any size opening and go into the interior of pastures, fields, and forest clearings that are as large as 15 to 20 acres. In the index, openings of 10 to 15 acres are considered optimum because they provide large transitional areas and are small enough for turkeys to use most of the interior area (fig. 8, sec. 3.4). Smaller or larger openings are assumed to limit one or more habitat requirements.

5.9 Grouse Habitat Index (GRS)

Grouse inhabit thickets and brushland. They feed on browse at all seasons and require dense cover for escape, nesting, brooding, and winter protection. Thus, the index is based on the variety and interspersion of early stages of succession as indicated by the proportion of total area in 6-inch pole stands and the frequency and size of openings. The proportion of pole-6 stands is a good indicator of seedling and sapling habitats as well.

(Eq. 142,S through 144.1,T)

As the proportion of area in 6-inch pole habitat increases to 20 percent, the index for grouse habitat type (GRH) increases to 1 (fig. 31). For a given area in 6-inch pole habitats, the size and frequency of openings affect the opportunity for use by the grouse. The index for grouse openings (GRO) increases as the size of openings decreases and their dispersion increases (fig. 32). These changes are indicated by the distribution of opening sizes (OPS).

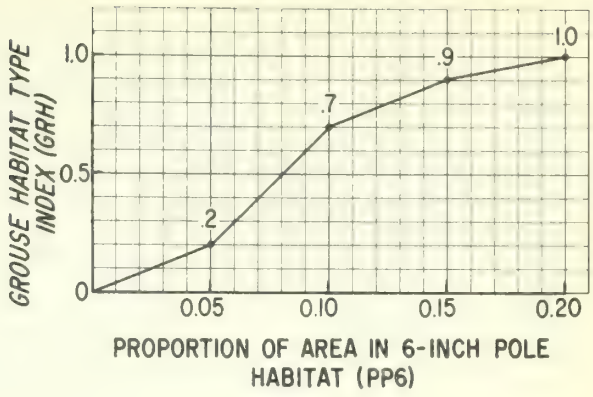


Figure 31.--Grouse habitat type index versus the proportion of area in 6-inch pole habitat.

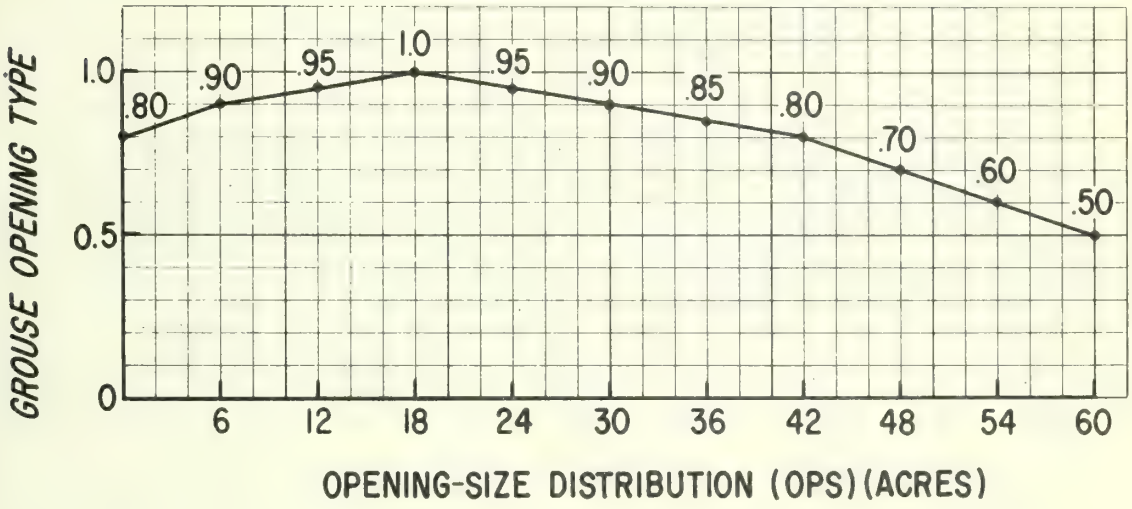


Figure 32.--Grouse opening type versus the distribution of size of openings (OPS).

5.10 Black Bear Habitat Index (BEAR)

Bears are omnivorous, using food from a variety of habitats at different times of the year. During the fall, they need large quantities of hard mast, and in the spring and warm months they feed on soft mast, grubs, insects, and small animals from seedling habitats. Bears use dense thickets for cover, and log and tree cavities for winter dens. The index includes habitat combinations that enhance these requirements for black bear.

(Eq. 128,S through 131.1,T)

Small areas of old-growth habitat, if well distributed and protected from disturbance, can provide enough cavities for winter dens. Den requirements are assumed to be satisfied when about 10 percent of the total area is in old-growth habitat (fig. 33). A decline in old growth below 10 percent rapidly reduces the probability of tree dens being present. This index for dens (DDT) has a base of 0.2 because some winter dens are in rock cavities, windfalls, and dense thickets.

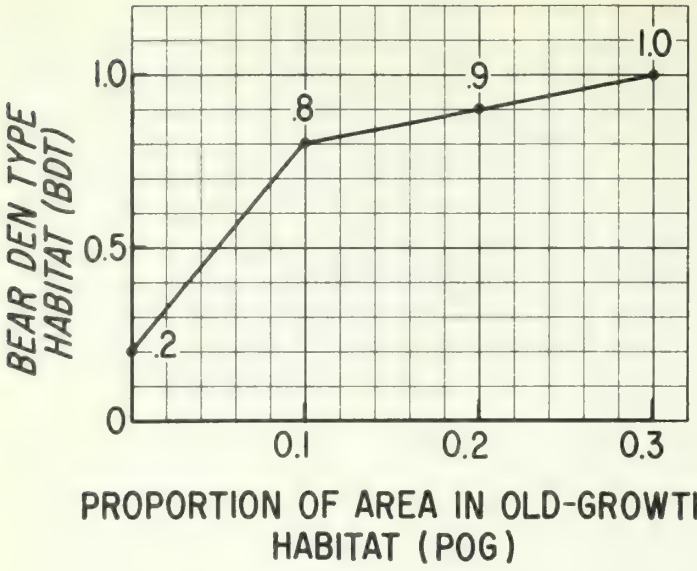


Figure 33.--Bear den type habitat the proportion of area in old g

Spring and summer foods and cover depend on the proportion of seedling and sapling habitats (fig. 34). The supply of hard mast is indicated by the proportion of area in 8-inch and 10-inch poles and mature timber (fig. 35). Of the three components of the index, hard mast is possibly the most restrictive. This index declines rapidly when the proportion of mast-producing habitats declines below 30 percent.

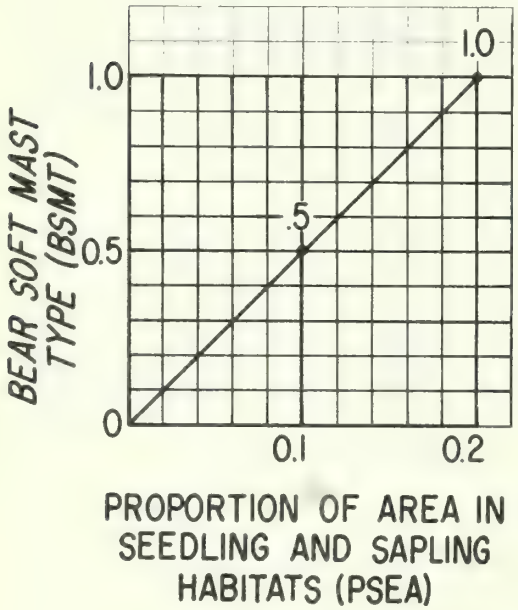


Figure 34.--Index of habitats for soft mast for bear versus the proportion of area in seedlings and saplings.

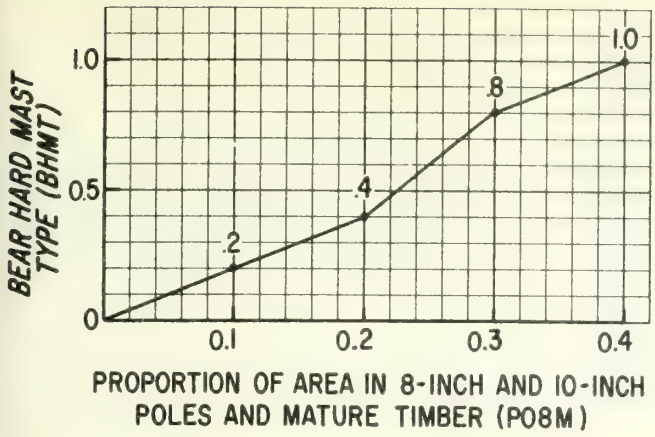


Figure 35.--Index of hard mast for black bear versus the proportion of area in mast-producing habitats.

5.11 Indices for Four Woodpeckers (PIL, FLIC, HAR, DON)

The nesting and habitat requirements for four woodpeckers are described by Conner and Adkisson (1976) and Conner and others (1975). These reports discuss the relative attractiveness of different habitats to these birds. As the proportional distribution of habitats changes, the index of attractiveness for each bird to the overall area varies. The authors suggest that the choice of habitat for nesting depends more on the prevalence of a habitat than on the woodpecker's preference. This question can be resolved by continuing to monitor the preference of these birds for habitats in relation to the distribution of habitats. The indices are to be adjusted as new data become available.

(Eq. 149,S through 154.1,T and 159,S, 159.1,T)

The index for pileated woodpeckers is based on the proportion of area in old-growth habitat (POG, fig. 36).

The index for hairy woodpeckers is based on the proportion of area in mature and old-growth habitats (PMO, fig. 37).

The index for downy woodpeckers is based on the proportion of area in pole-10 and mature timber habitats (PlM, fig. 38).

The index for the common flicker is more complex and is related to the proportion of area in seedling habitat (PSE, fig. 39), mature and old-growth habitats (PMO, fig. 40), and the distribution of opening sizes (OPS, fig. 41). Flickers often nest in rotting snags left in seedling and sapling habitats. These habitats also provide food for flickers. The proportion of area in mature and old growth is of minor importance if snags are left in seedling habitats. However, the short rotation modes of management limit the probability that snags will occur in the borders of seedling habitats because pole-10 and older habitats that have large dead trees are eliminated. Thus, the proportion of mature and old-growth habitats is an important component of the flicker index.

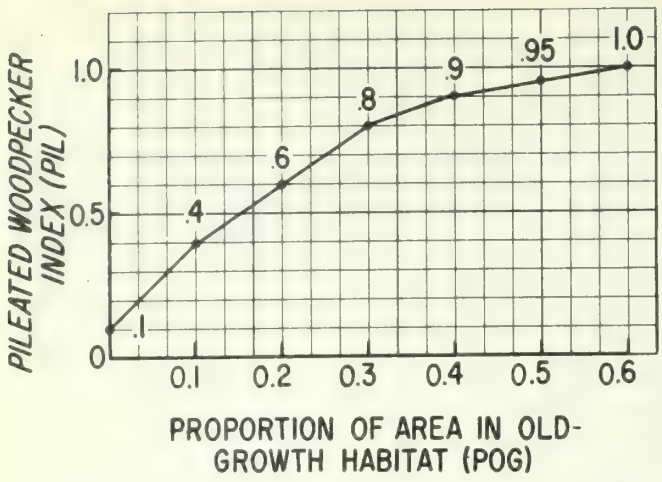
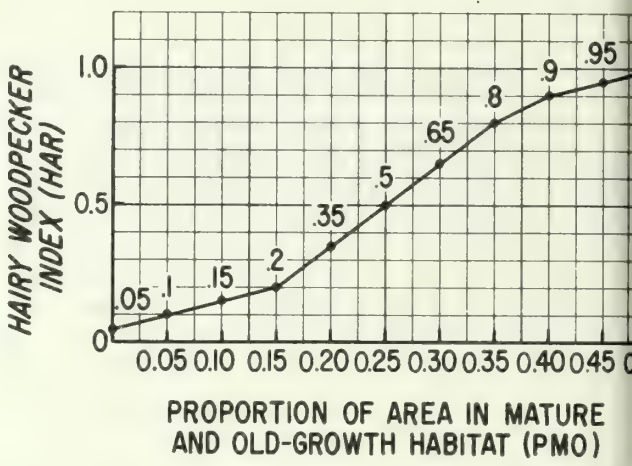


Figure 36.--Index of pileated woodpec habitat versus the proportion of ar in old-growth habitat.

Figure 37.--Index for hairy woodpecker habitat versus the proportion of area in mature and old-growth habitats.



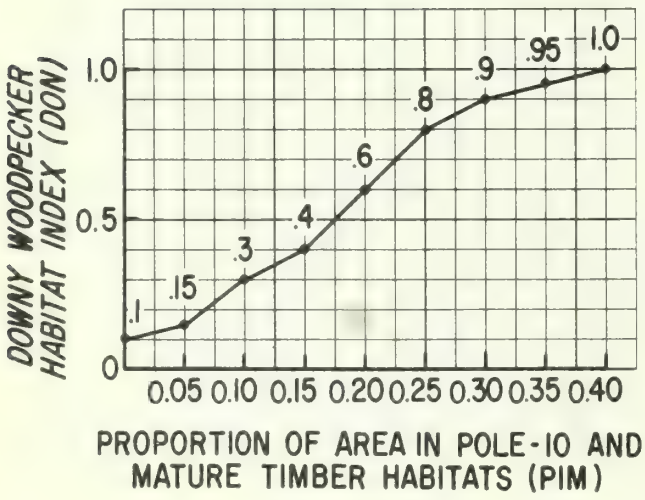
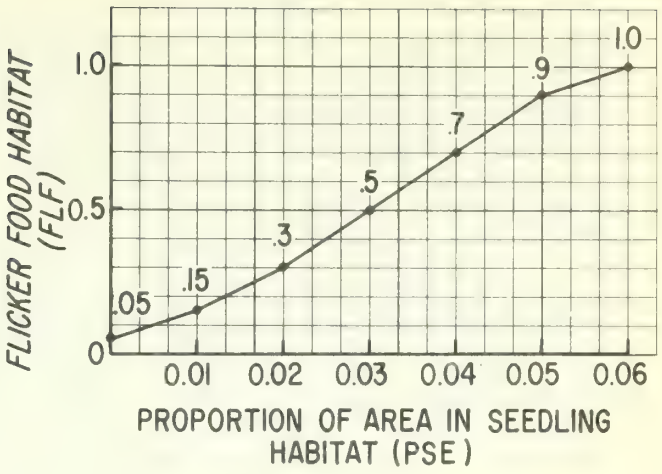


Figure 38.--Index of downy woodpecker habitat versus the proportion of area in pole-10 and mature timber habitats.



igure 39.--Flicker food habitat index versus the proportion of area in seedling habitat.

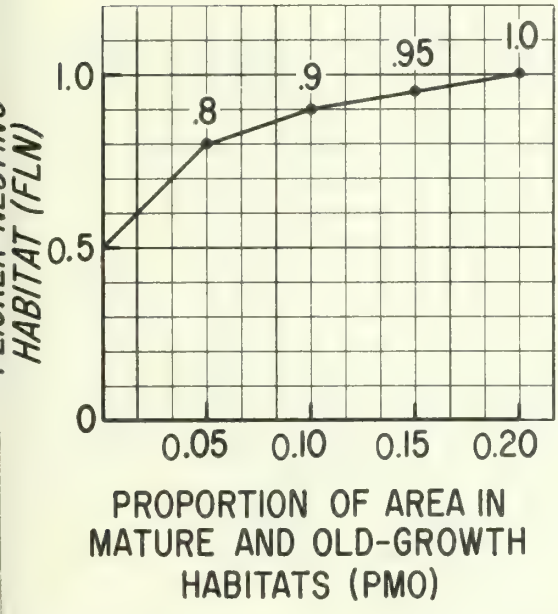
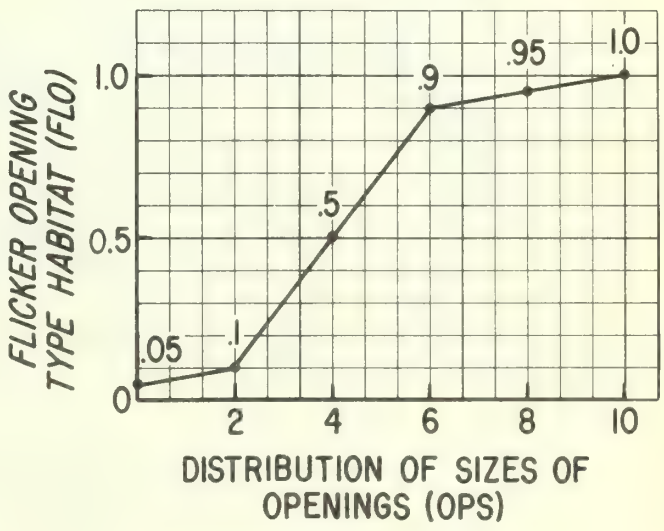


Figure 40.--Flicker nesting habitat versus the proportion of area in mature and old-growth habitats.



igure 41.--Flicker opening type habitat versus the opening-size distribution.

5.12 Indices for Four Groups of Birds (BLU, TWE, OVN, PWE)

The indices for four songbirds are based on the frequency of their occurrence in different habitats, as reported by Conner and Adkisson (1975) and other sources. Each of the four species represents a group of birds with a preference for a type of forest habitat: the eastern bluebird (BLU) for seedling habitat, the rufous-sided towhee (TWE) for sapling habitat, the ovenbird (OVN) for 6-inch pole timber, and the eastern wood pewee (PWE) for mature and old-growth habitat.

The bluebird-group index varies with the proportion of area in seedling habitat and the opening-size distribution (figs. 42 and 43). The towhee-group index is based on the proportion of area in sapling habitats (fig. 44). Size of opening is considered important for this group of birds but limited information is available (fig. 45). The ovenbird-group index is based on the proportion of area in pole-6 habitat (fig. 46) and probably should have included a variable for size of opening.

The index for the pewee group of birds is based on the proportion of area in mature and old-growth habitats (fig. 47). The size of openings affects the physical structure of succeeding habitats, especially the old-growth habitats. This probably affects the quality of bird habitat at all stages of succession (MacArthur and MacArthur 1961). More information on these relationships could improve the indices for songbirds.

(Eq. 145,S through 148.1,T and 155,S through 158.1,T)

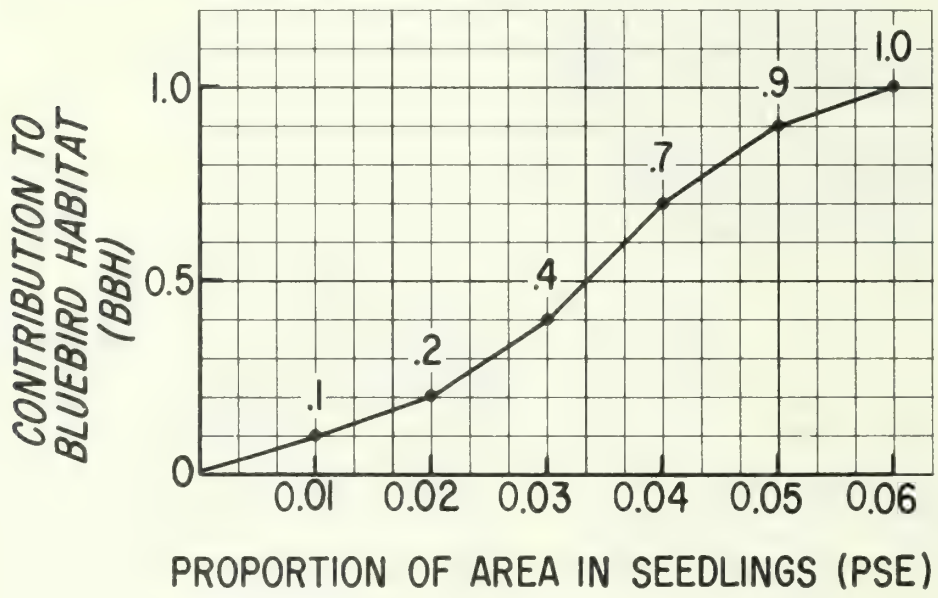


Figure 42.--Bluebird habitat index versus the proportion of area in seedling habitat.

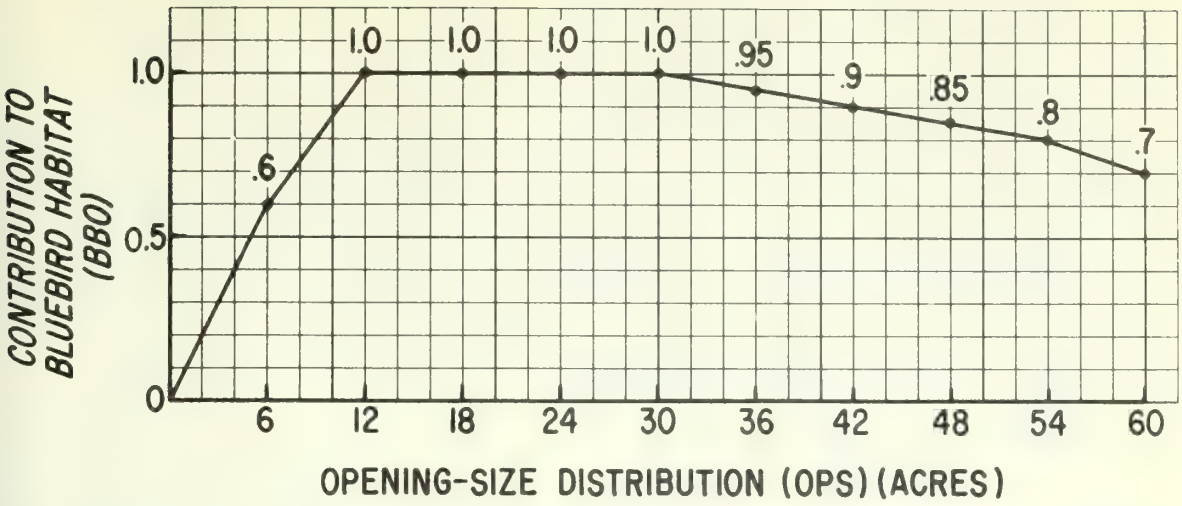


Figure 43.--Bluebird habitat index versus the distribution of size of openings.

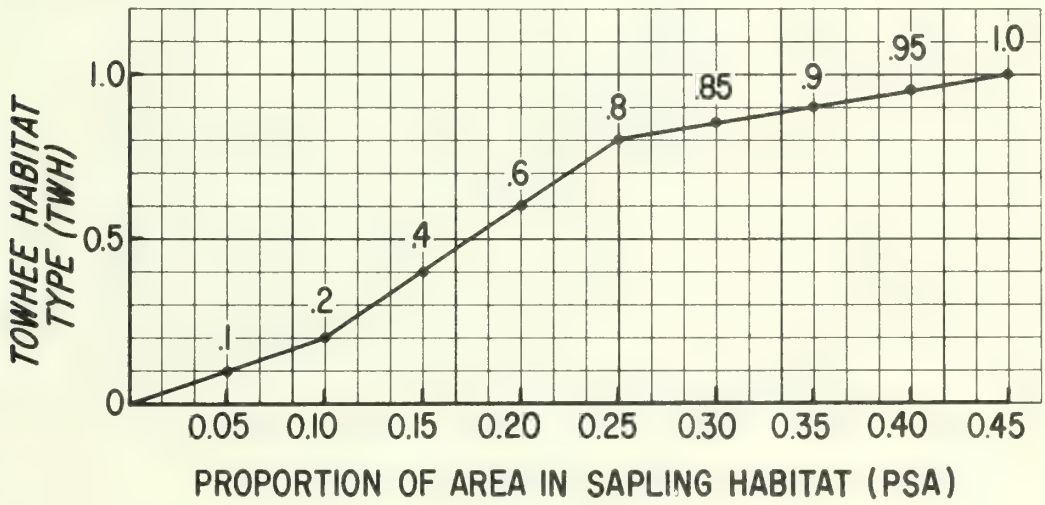


Figure 44.--Index of towhee habitat type versus the proportion of area in sapling habitat.

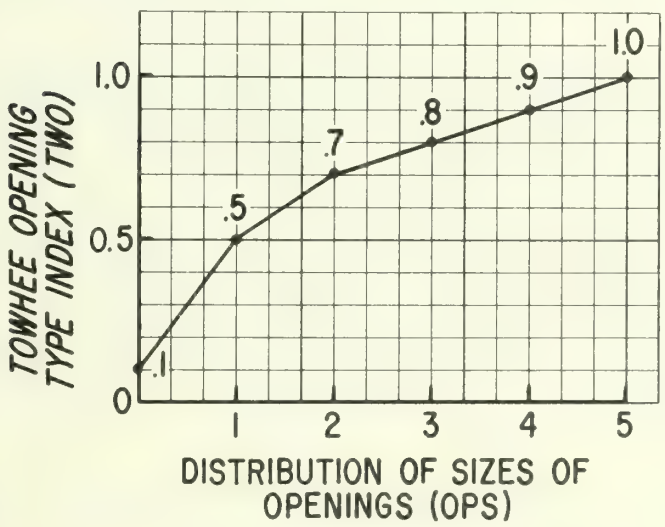


Figure 45.--The opening index for towhee habitat versus the distribution of size of openings.

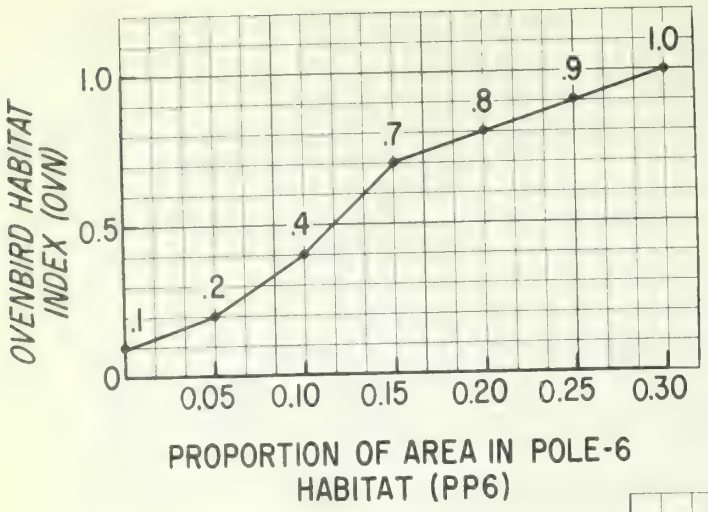


Figure 46.--Ovenbird habitat index versus the proportion of area in pole-6 habitat.

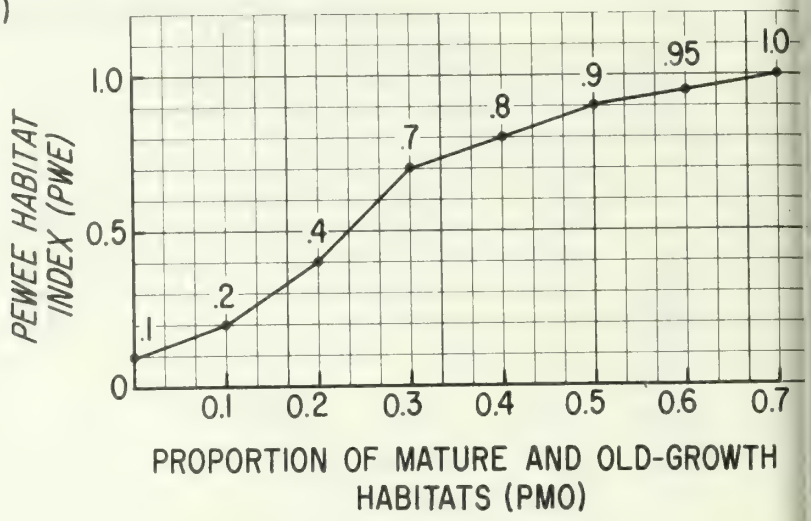


Figure 47.--Pewee habitat index versus the proportion of area mature and old-growth habitats.

5.13 Waterflow

Because relatively small increased flows of water are expected from typical modes of timber management, no index of change is included in the management system.

Forests delay the flow of water through the landscape by intercepting rainfall, storing water in plant tissues, and building absorptive soils. They divert some water back to the atmosphere by transpiration.

Removing the forest reduces the delays and increases the total streamflow (Worley and Patric 1971; Douglass and Swank 1972; Douglass 1974). The amount and duration of an increase in streamflow can be estimated from how much of the watershed is harvested, the amount of insolation, and the increase in flow from the harvested area the first year (Douglass and Swank 1975). Harvesting the entire watershed may increase flows by 8 to 18 inches the first year.[2/] However, flows rapidly decrease during the seedling habitat stage. Soon after the stands enter the sapling stage, streamflows subside to the levels before harvest.

2/One inch of increase in streamflow equals the volume of water required to cover the watershed to a depth of 1 inch.

For increases in streamflow to be measurable, 10 percent or more of the basal area in a watershed must be removed (fig. 48) (Douglass and Swank 1972). A particular opening of 25 acres may cause an increased flow from this opening for 5 to 10 years, but if this opening represents less than 10 percent of the managed area, very little, if any, measurable increase can be expected in waterflow from the total area. The fastest rate of harvest considered in the examples (table 1) is a rotation period of 20 years and amounts to an annual harvest of about 5 percent of the managed area per year. If large openings are used with these short rotations, overall streamflow could be increased. There is a need to develop appropriate algorithms to indicate streamflow for rotation periods of 5 to 300 years and varying sizes of openings.

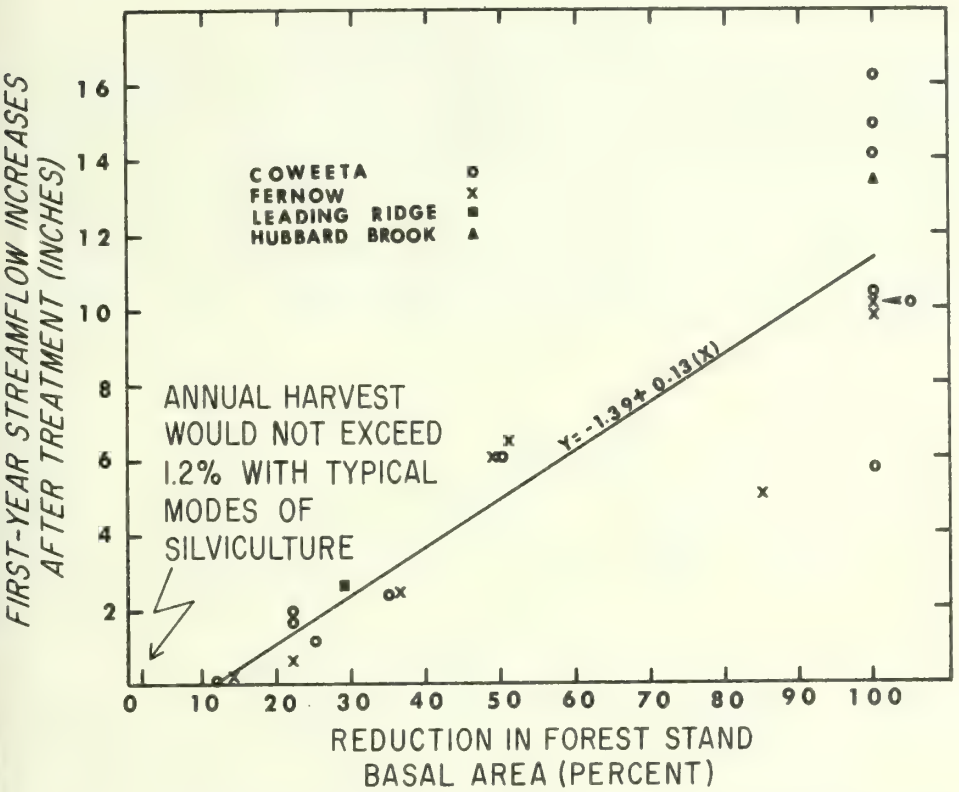


Figure 48.--Relationship between streamflow increase the first year after forest removal and the percentage reduction in forest stand (from Douglass and Swank 1972).

One variable for which we need information is the effect of roads and skid trails on the flow of water to streams. With appropriate data, algorithms could be developed to relate the size and frequency of openings to flows of water, nutrients, and other materials, as illustrated for the sediment index (sec. 2.2.3).

5.14 Nutrient Flow

At present, we do not know enough about nutrient flows to develop an index.

Forests delay the flows of nutrients through the landscape. The delays are reduced by the removal of trees and by increased movement of sediment. We do not know how many nutrients are lost immediately after harvest or how many are replaced before the next harvest. These questions are being investigated by many workers (Howell and others 1975; Vitousek and Reiners 1975). Appropriate indices can be developed when data become available.

The removal of wood from a forest necessarily removes some nutrients from the area. Losses are generally proportional to the amount of wood removed, but may vary with the kind of soil and the size of the woody materials. Removing leaves, roots, and small branches may remove more nutrients per unit weight of organic matter than the removal of large logs (Patric and Smith 1975; Stone 1975; Douglass and Swank 1976).

According to the preliminary information we have, the rates of harvest considered for DYNAST-TM (table 1) would not increase nutrient flows enough to limit future timber yields, degrade drinking water, or harm the biological productivity of streams (Douglass and Swank 1975).

More information might allow us to regulate distribution of forest habitats for desirable flows of nutrients and organic matter through streams. Energy and nutrients from leaves, branches, roots, and similar terrestrial organic matter are the primary sources of support for animals in many streams (Howell and others 1975). However, our knowledge about the delays in the flow of energy and material comes from small watersheds that are in a single state of organization. These studies are incomplete in that the kinds and amounts of delay are known for only a few habitats. Because of this lack of knowledge, the productivity of streams cannot be purposively influenced by regulating the combination of habitats in watersheds. When more knowledge is available, algorithms can be developed for the productivity of streams in the same way as for the potential timber index (sec. 5.2).

6. THE DYNAMICS OF SIX MODES OF MANAGEMENT: AN APPALACHIAN EXAMPLE

This section analyzes the model runs for six modes of management (table 1) applied to the Big Ivy watershed in North Carolina. A user may work from these illustrations to develop some intermediate modes that would be suitable for a similar area. Each mode is illustrated by one table and three computer plots. These illustrations are not described separately, since they have the same format. The variables are defined in appendix B and on the print and plot cards which have the equation numbers 167.1 through 168.3.

The first line at the top of each table or plot identifies the program, DYNAST-TM; the area, unit 16, Big Ivy, standard lands; the date and time the model was run, 1/07/77, 09:39; and the mode of management, as described in table 1. For example, 20/50 is a 20-year rotation with openings of 50 $\pm$ 12.5 acres. The page numbers are simply the sequence of printing by the computer.

The second and third lines in the tables name the variables; the fourth and fifth lines indicate the location of decimal points. For example, E +03 means the number should be multiplied by 10^3. The first column in the tables is time in years. Data are printed annually for the first 10 years, then at 40-year intervals.

The second line on the plots lists the variables (appendix B) and the symbols used in the plot. The scales for the plots are indicated in the next one or more lines. For example, the plots for the proportional distribution of habitats have two scales. The proportion of seedling habitats is plotted on a scale of 0 to 40 percent. The proportions of saplings, pole-6, pole-8, pole-10, mature and old-growth habitats are scaled from 0 to 80 percent. All of the benefit and impact plots are scaled from 0 to 1.

Time in years is plotted at the bottom (first column) of the charts. The variables are plotted annually for the first 10 years and then at 4-year intervals. Time begins at the time of the inventory. The plotted 170-year period is long enough for the faster rates of harvest to bring the distribution of habitats and the indices for benefits to a steady state, although the 300/1 mode continues to oscillate for about 550 years. The 170-year period seems adequate for making decisions about the next 10 to 20 years.

Groups of letters above the chart show coincident indices. The first letter of each group appears on the plot; the other indices are at the same level as the plotted symbol. These groups must not be confused with indices at the top line (value 1) of the plot.

6.1 Mode 20/50: 20-year Rotation and 50-acre Openings (table 4 and figs. 49, 50, 51)

This extreme mode is not used for hardwood forests at this time. Forty or more years ago some hardwood stands were harvested for fuelwood when 20 to 50 years old (Graves 1911; Frothingham 1912, 1917; Spaeth 1928). Hardwood stands in the Eastern United States can be harvested a number of times with 20-year rotations because new stands regenerate from sprouts and seeds (Sander and Clark 1971). However, changes in species composition and productivity might develop after many rotations. This mode is illustrated because it is extreme, it is possible for some number of rotations, and it may be considered for the production of fuelwood and organic feedstocks for the chemical industry.

The old-growth, mature timber, and 8- and 10-inch pole stands are essentially liquidated by year 15 (table 4, fig. 49). During the first 10 years, removals (PTI, table 4) exceed three times the volumes that can be harvested at the steady state. Later, at equilibrium, annual yields in total cubic volume are still 1.38 times those expected for 50-year rotations. However, the harvest would come from the sapling and pole-6 habitats and most of the trees would be less than 5 inches in diameter.

Timber does not show on the plot of benefits because it exceeds 1 and is off the top (fig. 50). The other conditions are extremely unfavorable. Sediment flows are heavy and wildlife populations, except for some songbirds, would be very low (fig. 51).

TIME	OGS VOG	MTS VMT	P1S VP1	P8S VP8	P6S VP6	SAS VSA	PTI VT	OG MT	P1 P8	P6 SA	SE SEMT	DEER SQU	TUR GRS	VIS UGL
E+00	E+00 E+03	E+00 E+03	E+00 E+03	E+00 E+03	E+00 E+03	E+00 E+03	E+00 E+03	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00
.0	185.00 438.34	134.80 261.65	.00 .00	.00 .00	.00 .00	.00 .00	2.1715 700.0	370.00 500.80	1808.0 740.0	1843.0 1254.0	200.0 .80586	.29772 .44709	.38134 .66667	.49983 .12272
1.	64.91 514.87	254.89 403.61	.00 .00	.00 .00	.00 .00	.00 .00	2.8492 918.5	276.08 496.91	1769.5 809.7	1764.0 1261.8	337.8 .87901	.46929 .35899	.38476 .66667	.40967 .07206
2.	24.24 413.76	136.72 584.64	158.84 61.71	.00 .00	.00 .00	.00 .00	3.2886 1060.1	184.89 439.52	1731.4 869.9	1690.7 1299.0	500.4 .84151	.56667 .27344	.38034 .66667	.08983 .23812
3.	9.90 284.59	94.85 548.57	215.05 265.66	.00 .00	.00 .00	.00 .00	3.4087 1098.8	119.18 368.53	1654.1 921.6	1623.7 1367.3	662.4 .88212	.56667 .21087	.36826 .66667	.08048 .07973
4.	4.78 184.27	74.66 466.94	240.36 451.39	.00 .00	.00 .00	.00 .00	3.4204 1102.6	74.34 305.92	1530.0 965.7	1563.8 1464.5	811.6 .76219	.56667 .16974	.35042 .66667	.07286 .45672
5.	2.84 116.66	60.54 388.65	256.42 589.20	.00 .00	.00 .00	.00 .00	3.3953 1094.5	46.78 252.82	1371.8 1003.3	1511.1 1586.7	943.3 .90300	.56667 .14389	.32869 .66667	.06668 .01000
6.	1.97 73.63	48.16 320.75	269.67 687.67	.00 .00	.00 .00	.00 .00	3.3566 1082.0	29.74 206.65	1192.1 1035.1	1466.2 1729.5	1056.5 .77839	.56667 .12292	.29664 .66667	.06155 .43242
7.	1.46 46.83	36.33 261.37	282.01 759.53	.00 .00	.00 .00	.00 .00	3.3122 1067.7	19.17 165.00	999.6 1062.2	1429.0 1888.6	1152.2 .73221	.52604 .10575	.25778 .66667	.05717 .50169
8.	1.06 30.17	24.71 207.78	277.57 814.53	16.45 .00	.00 .00	.00 .00	3.2649 1052.5	12.52 126.19	799.8 1085.3	1399.6 2060.2	1232.2 .85885	.43557 .09262	.21735 .66667	.05335 .17049
9.	.72 19.65	14.08 157.94	129.89 782.57	175.11 63.77	.00 .00	.00 .00	3.1764 1023.9	8.19 90.14	603.1 1097.1	1377.8 2240.9	1298.5 .90468	.31187 .07750	.17590 .66667	.04995 .01000
10.	.44 12.83	7.77 113.01	80.48 612.14	231.11 237.76	.00 .00	.00 .00	3.0269 975.7	5.31 61.54	445.2 1059.2	1363.4 2427.9	1353.3 .77497	.21272 .06082	.13381 .66667	.04690 .43755
50.	.00 .00	.03 .10	.54 1.65	8.46 20.94	135.39 242.35	175.38 181.20	1.3843 446.2	.03 .08	1.6 25.4	406.2 4683.3	1598.9 .82176	.05697 .00085	.00169 .22337	.03220 .31515
90.	.00 .00	.00 .10	.54 1.65	8.46 20.94	135.38 242.33	175.42 181.22	1.3843 446.2	.03 .08	1.6 25.4	406.1 4683.0	1599.0 .84782	.05697 .00085	.00169 .22333	.03220 .21349
130.	.00 .00	.04 .11	.54 1.65	8.46 20.94	135.37 242.32	175.39 181.22	1.3843 446.2	.03 .08	1.6 25.4	406.1 4682.8	1599.0 .77048	.05697 .00085	.00169 .22331	.03220 .44428
170.	.00 .00	.03 .09	.54 1.65	8.46 20.93	135.37 242.30	175.40 181.23	1.3842 446.2	.03 .08	1.6 25.4	406.1 4682.6	1599.0 .78443	.05697 .00085	.00169 .22329	.03220 .42336

PSE=S,PSA=A,PP6=6,PP8=8,PP1=1,PMT=M,POG=O

Figure 49.

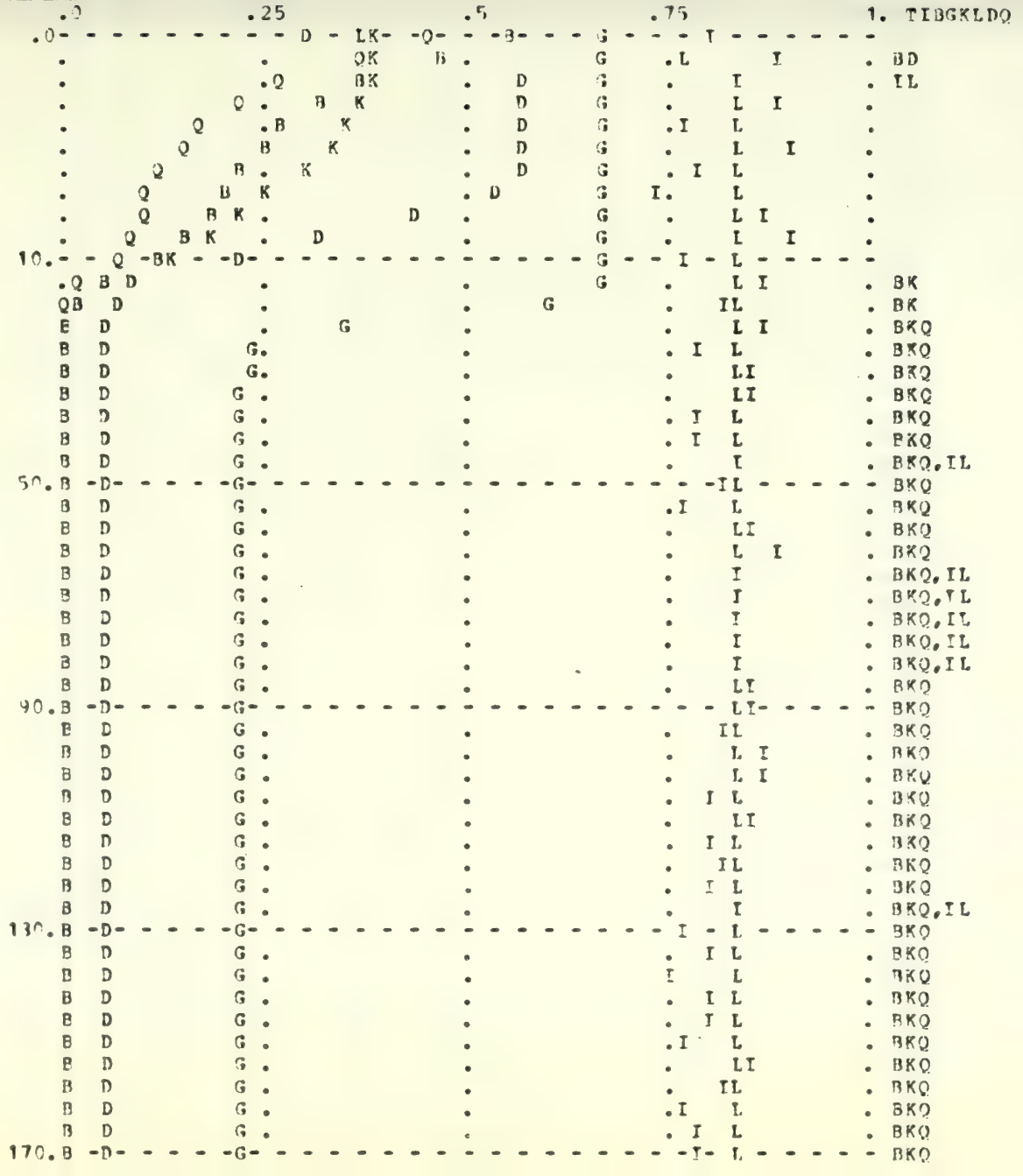


Figure 50.

VIS=V,UGL=U,OVN=O,PIL=P,FLIC=F,DON=N,TWE=W,PWE=E,HAR=H

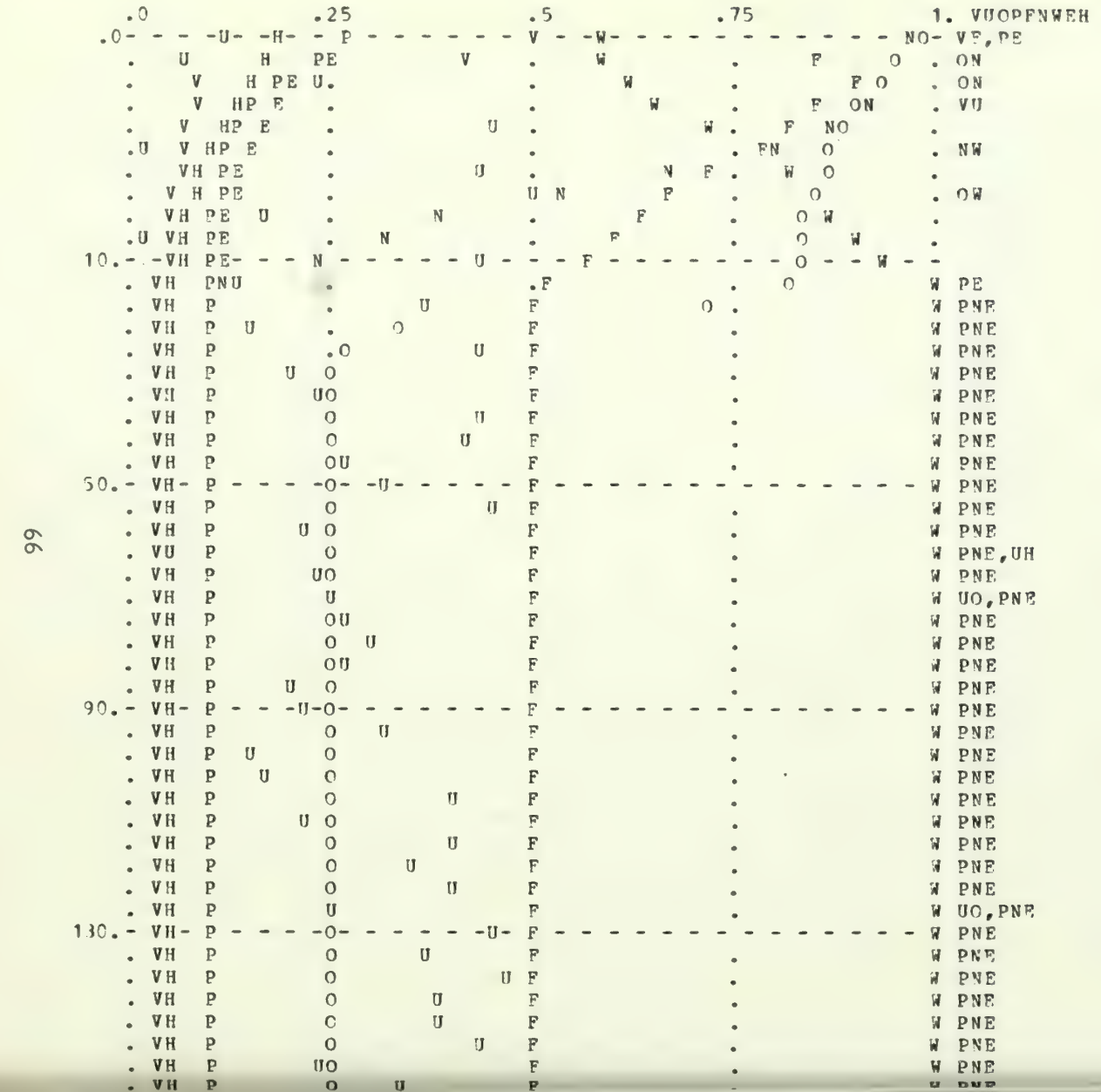


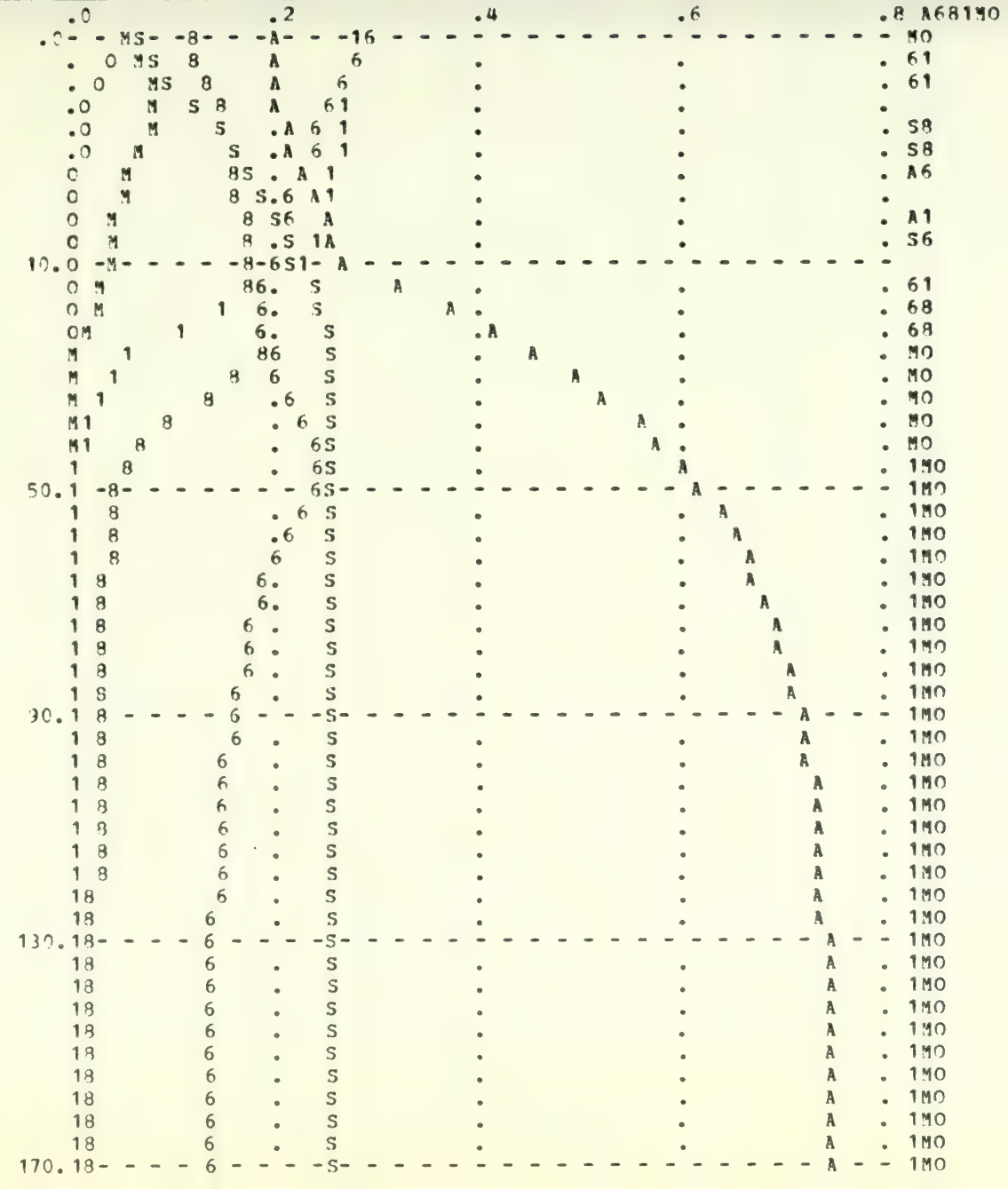
Figure 51.

6.2 Mode 40/40: 40-year Rotation and 40-acre Openings (table 5 and figs. 52, 53, 54)

This mode may be considered for the production of pulpwood, fuelwood, and organic feedstocks. At the steady state, most of the harvest would come from the 6- and 8-inch pole stands and most of the trees would be less than 8 inches in diameter (table 5). The old-growth, mature, and 10-inch pole stands are liquidated after 46 years (fig. 52). The liquidation of these old stands results in a potential timber index as large as 1.9 for the first 10 years. At the steady state, timber yields are about the same as for 50-year rotations, which is the age for culmination of mean annual increment for cubic volume.

Timber-related benefits are not greatly different from those for the 20/50 mode. The largest differences are increases in the indices for grouse and the ovenbird group (figs. 53 and 54), an increase in ugliness, and a small decrease in sediment.

TIME	OGS VOG	MTS VMT	P1S VP1	P8S VP8	P6S VP6	SAS VSA	PTI VT	OG MT	P1 P8	P6 SA	SE SEMT	DEER SQU	TUR GRS	VIS UGL
E+00	E+00 E+03	E+00 E+03	E+00 E+03	E+00 E+03	E+00 E+03	E+00 E+00	E+00 E+03	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00
.0	159.90 379.47	.00 .00	.00 .00	.00 .00	.00 .00	0. 0.	1.1772 379.47	344.90 366.00	1808.0 740.0	1843.0 1254.0	200.00 .58645	.38529 .42355	.36448 .81667	.47699 .23071
1.	68.93 470.45	90.97 28.00	.00 .00	.00 .00	.00 .00	0. 0.	1.5463 498.45	264.52 442.30	1769.5 809.7	1753.9 1255.6	250.35 .63377	.50076 .34814	.37793 .81667	.49590 .31354
2.	29.63 396.04	130.27 176.56	.00 .00	.00 .00	.00 .00	0. 0.	1.7763 572.60	184.83 488.72	1737.2 869.9	1690.2 1268.5	316.55 .61300	.58294 .27339	.38722 .81667	.42602 .46943
3.	16.26 285.17	143.64 319.54	.00 .00	.00 .00	.00 .00	0. 0.	1.8759 604.71	126.25 496.47	1710.2 921.5	1621.8 1294.4	385.22 .63539	.66168 .21844	.39126 .81667	.26278 .64691
4.	10.75 196.98	149.15 422.15	.00 .00	.00 .00	.00 .00	0. 0.	1.9206 619.13	86.52 474.70	1687.7 965.5	1558.9 1332.8	449.81 .56117	.73333 .18116	.39123 .81667	.08474 .72589
5.	7.62 135.43	152.28 489.67	.00 .00	.00 .00	.00 .00	0. 0.	1.9392 625.10	59.77 433.38	1669.0 1002.6	1501.5 1382.2	507.49 .64592	.73333 .15607	.38836 .81667	.08127 .63112
6.	5.22 93.49	113.22 526.46	41.46 5.99	.00 .00	.00 .00	0. 0.	1.9418 625.94	41.24 380.13	1653.1 1033.7	1449.5 1440.8	557.45 .56966	.73333 .13868	.38361 .81667	.07831 .72023
7.	3.60 64.43	89.07 483.11	67.23 70.07	.00 .00	.00 .00	0. 0.	1.9159 617.61	28.41 329.23	1629.2 1059.6	1402.9 1506.7	599.83 .54483	.73333 .12665	.37749 .81667	.07572 .73678
8.	2.78 44.52	79.27 423.13	77.85 140.14	.00 .00	.00 .00	0. 0.	1.8854 607.79	19.98 289.91	1589.8 1080.9	1361.5 1574.4	635.46 .62289	.73333 .11874	.37030 .81667	.07343 .66566
9.	2.37 31.39	73.58 373.47	83.95 194.59	.00 .00	.00 .00	0. 0.	1.8596 599.46	14.60 260.55	1538.1 1098.2	1325.2 1654.2	665.04 .64674	.73333 .11369	.36233 .81667	.07135 .62989
10.	2.15 22.97	69.09 335.57	88.67 234.15	.00 .00	.00 .00	0. 0.	1.8386 592.68	11.19 237.99	1478.3 1112.1	1293.8 1733.0	689.48 .56788	.73333 .11050	.35377 .81667	.06943 .72141
50.	.00 .04	.28 1.29	5.70 19.71	88.05 238.07	65.87 130.98	0. 0.	1.2101 390.09	.05 .94	18.3 273.7	1504.3 3959.0	799.47 .60109	.07775 .00916	.01832 .81667	.03425 .69836
90.	.00 .03	.16 .62	3.25 10.20	50.72 130.41	105.77 213.59	0. 0.	1.1008 354.85	.04 .48	9.9 154.1	1014.4 4577.1	799.50 .61666	.07571 .00514	.01028 .74904	.03324 .67500
130.	.00 .03	.13 .49	2.61 8.07	40.92 103.35	116.25 232.04	0. 0.	1.0671 343.98	.03 .38	7.8 123.3	884.9 4739.2	799.50 .56554	.07522 .00411	.00822 .69695	.03298 .72297
170.	.00 .02	.12 .46	2.44 7.50	38.33 96.25	119.01 236.75	0. 0.	1.0578 340.99	.03 .36	7.3 115.1	850.7 4781.6	799.50 .57277	.07509 .00384	.00768 .67951	.03292 .71816


.0 .2 .4 .6 .8 A68IMO
.0- - MS- -8- - -A- - -16 - MO
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. O MS 8 A 6 . . . 61
.O M S 8 A 61 . . .
.O M S .A 6 1 . . . S8
.O M S .A 6 1 . . . S8
O M 8S . A 1 . . . A6
O M 8 S.6 A1 . . .
O M 8 S6 A . . . A1
O M 8 .S 1A . . . S6
10.O -M- - - - -8-6S1- A -
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O M 1 6. S A . . . 68
OM 1 6. S .A . . . 68
M 1 86 S . A . . . MO
M 1 8 6 S . A . . . MO
M 1 8 .6 S . A . . . MO
M1 8 . 6 S . A . . . MO
M1 8 . 6S . A . . . MO
1 8 . 6S . A . . . 1MO
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1 8 .6 S . . A . . 1MO
1 8 6 S . . A . . 1MO
1 8 6. S . . A . . 1MO
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90.1 8 - - - - 6 - - - -S- - - - - - - - - - - - - - - - - - - A - - - 1MO
1 8 6 . S . . A . . 1MO
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130.18- - - - 6 - - - - -S- A - - 1MO
18 6 . S . . A . 1MO
18 6 . S . . A . 1MO
18 6 . S . . A . 1MO
18 6 . S . . A . 1MO
18 6 . S . . A . 1MO
18 6 . S . . A . 1MO
18 6 . S . . A . 1MO
18 6 . S . . A . 1MO
18 6 . S . . A . 1MO
170.18- - - - 6 - - - - -S- A - - 1MO

Figure 52.

PTI=T,SEMT=I,BEAR=B,GRS=G,TUR=K,BLU=L,DEER=D,SQU=Q

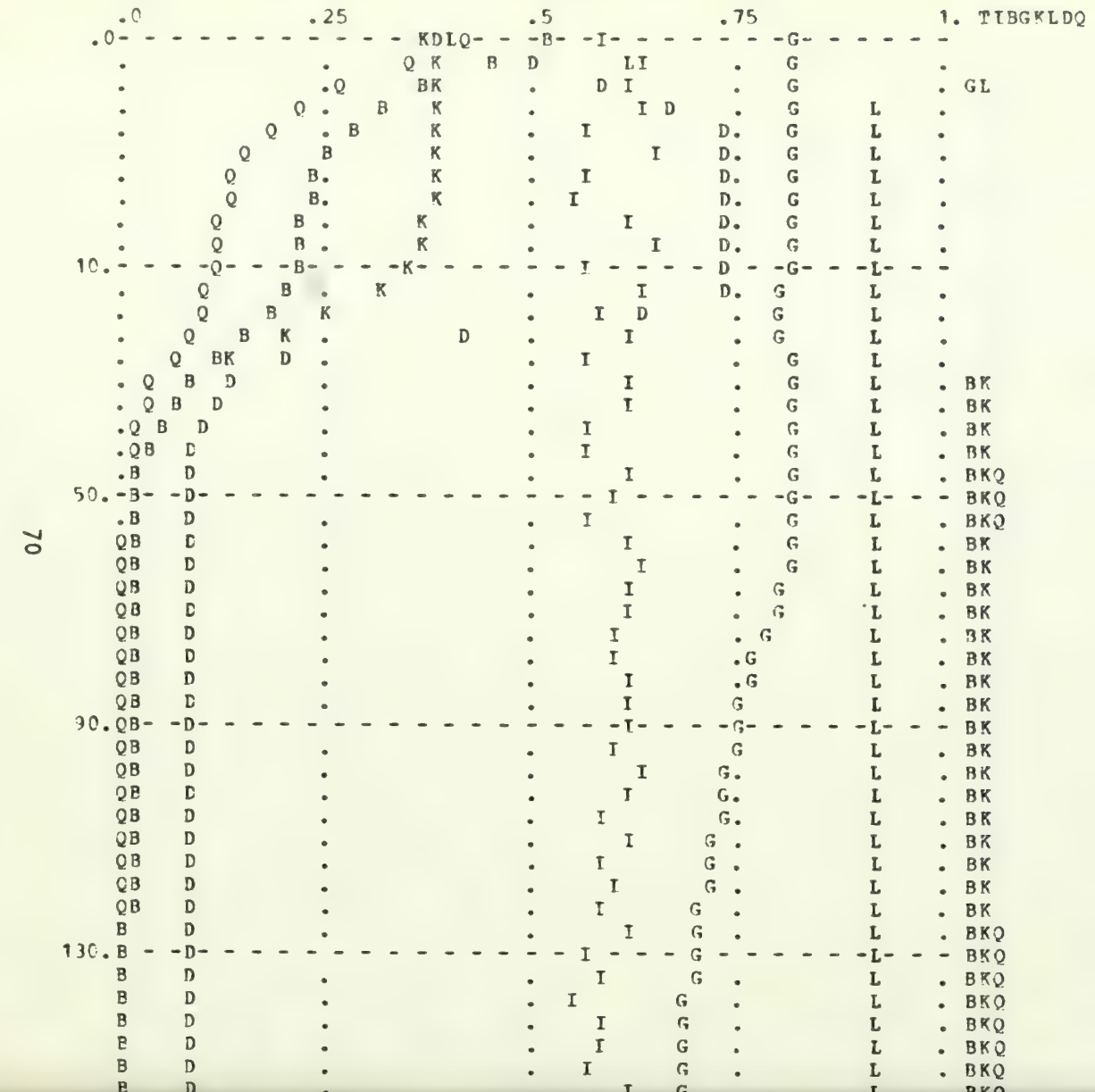

Figure 53.

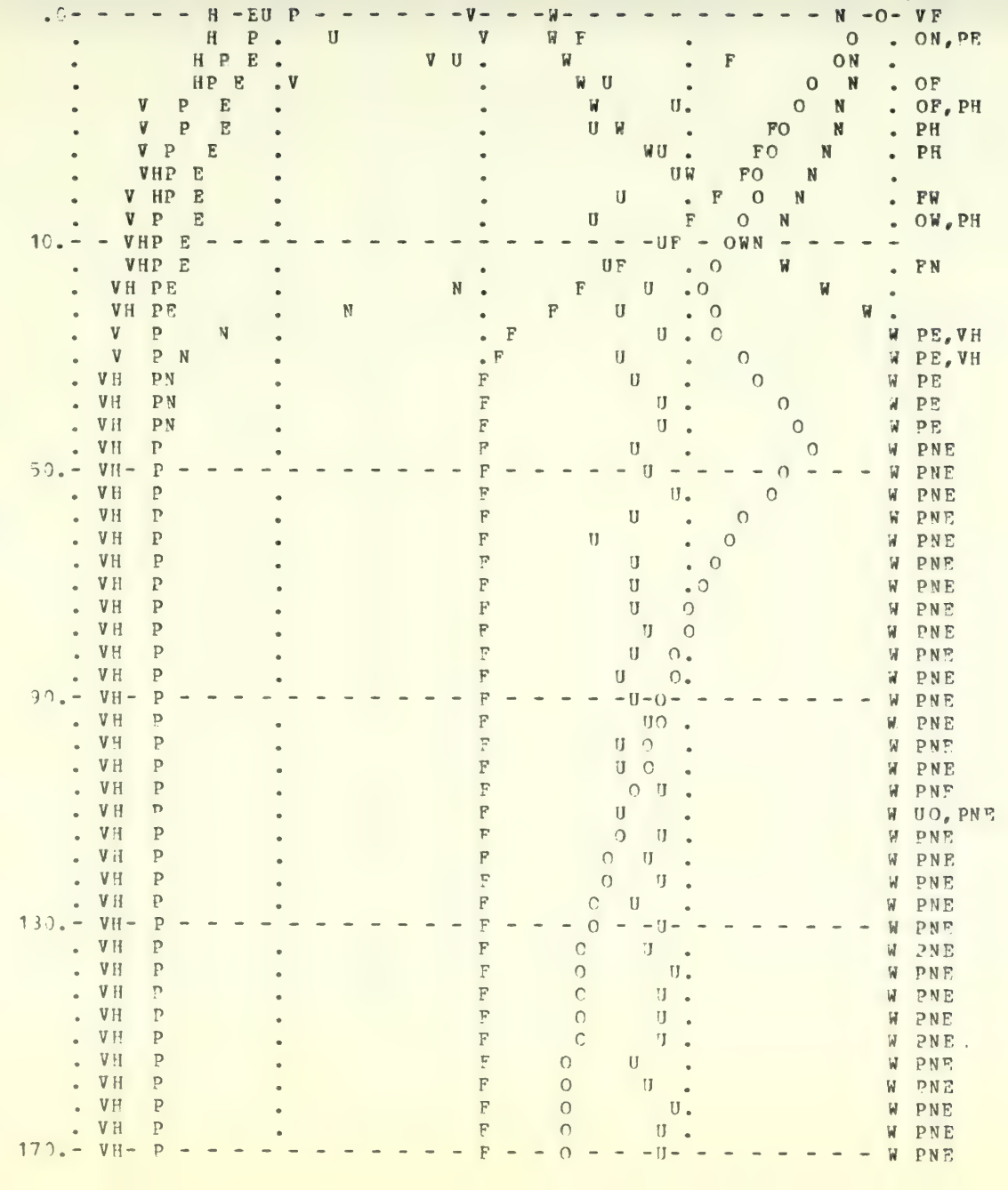

Figure 54.

6.3 Mode 80/25: 80-year Rotation and 25-acre Openings (table 6 and figs. 55, 56, 57)

Doubling the rotation period from 40 to 80 years lowers the potential timber index only about 0.07 points (table 6). However, the habitat indices are increased for grouse, deer, turkey, bear, squirrel (fig. 56), and flicker (fig. 57). Sediment is reduced a small amount despite smaller openings because less area is harvested annually. A number of indices remain below 0.25, generally because of the absence of old growth (fig. 55).

An 80-year rotation has been considered desirable for eastern hardwood forests because most trees are harvested from mature timber and 10-inch pole stands (table 6). These trees are large enough to make lumber and some high-quality furniture blanks. Eighty years is about the shortest rotation for supporting industries that require large pieces of lumber.

	VOG	VMT	VP1	VP8	VP6	VSA	VT	MT	PB	JA	GFMT	SOU	GPS	UGL
E+00	E+00 E+03	E+00 E+03	E+00 E+03	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+03	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00
.0	79.950 190.08	.000 .00	.000 .000	0. 0.	0. 0.	0. 0.	.5897 190.08	264.95 366.00	1808.0 740.0	1843.0 1254.0	200.00 .47123	.46847 .34855	.50116 .94167	.44515 .24461
1.	79.950 252.65	.000 .00	.000 .000	0. 0.	0. 0.	0. 0.	.7838 252.65	229.39 444.34	1769.5 809.7	1763.9 1252.5	206.63 .51188	.48695 .31519	.52000 .94167	.45114 .25124
2.	53.314 305.02	26.636 .00	.000 .000	0. 0.	0. 0.	0. 0.	.9462 305.02	182.34 518.69	1737.2 869.9	1689.9 1253.3	224.62 .49240	.53711 .27105	.53758 .94167	.45814 .29706
3.	27.280 273.47	52.670 53.20	.000 .000	0. 0.	0. 0.	0. 0.	1.0134 326.67	135.99 582.79	1710.2 921.5	1620.9 1258.0	246.65 .51338	.59854 .22757	.55000 .94167	.44931 .34162
4.	19.463 210.76	60.487 122.85	.000 .000	0. 0.	0. 0.	0. 0.	1.0349 333.61	102.44 628.12	1687.7 965.4	1556.5 1267.0	268.92 .45482	.64240 .19610	.55000 .94167	.42281 .41231
5.	17.172 160.78	62.778 175.46	.000 .000	0. 0.	0. 0.	0. 0.	1.0431 336.24	80.94 657.59	1669.0 1002.3	1496.6 1280.0	289.60 .52310	.67123 .17593	.55000 .94167	.39353 .43522
6.	16.545 127.64	63.405 209.81	.000 .000	0. 0.	0. 0.	0. 0.	1.0468 337.45	67.86 676.15	1653.4 1033.0	1441.1 1296.4	307.92 .46038	.69677 .16366	.55000 .94167	.37188 .50292
7.	16.409 107.18	63.541 230.92	.000 .000	0. 0.	0. 0.	0. 0.	1.0488 338.10	60.12 687.71	1640.5 1058.3	1389.8 1315.8	323.72 .44403	.71880 .15640	.55000 .94167	.35079 .55255
8.	16.409 94.97	63.541 243.52	.000 .000	0. 0.	0. 0.	0. 0.	1.0500 338.49	55.61 694.87	1629.8 1078.6	1342.5 1337.4	337.10 .50173	.73745 .15217	.55000 .94167	.32210 .57207
9.	16.441 87.83	63.509 250.90	.000 .000	0. 0.	0. 0.	0. 0.	1.0508 338.73	53.01 699.30	1620.8 1094.7	1298.9 1360.9	348.30 .52385	.75306 .14973	.55000 .94167	.29918 .59877
10.	16.473 83.71	63.477 255.18	.000 .000	0. 0.	0. 0.	0. 0.	1.0513 338.89	51.53 701.99	1613.2 1107.0	1259.0 1385.6	357.59 .45922	.76602 .14834	.55000 .93573	.28083 .66624
50.	11.718 58.24	68.232 273.70	.000 .000	0. 0.	0. 0.	0. 0.	1.0297 331.94	36.20 536.00	1398.0 988.7	997.5 2119.6	399.74 .48105	.82477 .13396	.50266 .85873	.18739 .74553
90.	1.829 8.81	63.673 252.31	14.448 50.440	0. 0.	0. 0.	0. 0.	.9665 311.56	5.55 192.57	1330.3 1090.8	1131.4 2325.4	399.75 .49587	.82479 .10520	.44951 .89814	.16239 .73608
130.	1.583 7.52	55.278 216.53	23.089 83.410	0. 0.	0. 0.	0. 0.	.9538 307.47	4.76 166.30	1180.6 1164.4	1180.4 2379.3	399.75 .45769	.82479 .10293	.42786 .91258	.15699 .76043
170.	1.508 7.14	52.745 205.75	25.697 93.089	0. 0.	0. 0.	0. 0.	.9492 305.98	4.53 158.37	1135.7 1189.5	1194.2 2393.4	399.75 .46241	.82479 .10181	.42068 .91664	.15557 .75742

```
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        .0              .2              .4              .6              .8 A681MO
    .0- -OMS- -8- - -A- - -16 - - - - - - - - - - - - - - - - - - - - -
      . O S   8      A      6          .               .               . 61,SM
      . O  SM    8     A     6         .               .               . 61
      . O   SM    8    A    61         .               .               .
      .O    SM    8    A   6 1         .               .               .
      .O     SM    8   A   6 1         .               .               .
      .O     SM    8   A 6 1           .               .               .
      .O      S    8   A6  1           .               .               . SM
      .O      S     8 .A   1           .               .               . A6,SM
      .O      S     8 6A   1           .               .               . SM
    10.-O- - - S - -8-6A -1- - - - - - - - - - - - - - - - - - - - - - SM
      .O      MS    6 . A 1           .               .               . 68
      .O      MS   68 .   1A          .               .               .
      .O      MS   68 .   1 A         .               .               .
      .O      MS 6 8 .   1  A         .               .               .
      .O      MS 68  .   1   A        .               .               .
      .O      MS 68  . 1      A       .               .               .
      .O     M S 68  . 1      A       .               .               .
      O      M S 68  . 1       A      .               .               .
      O      M S  6  . 1       A      .               .               . 68
    50.O - - M -S- 6 - 1 - - - -A- - - - - - - - - - - - - - - - - - - 68
      O      M   S  6  .1        A     .               .               . 68
      O     M    S  6  .1         A    .               .               . 68
      O     M    S  6  .1         A    .               .               . 68
      O    M     S  6  .1         A    .               .               . 68
      O    M     S  86 .1         A    .               .               .
      O  M       S  86 .1          A   .               .               .
      O  M       S  86 .1          A   .               .               .
      O M        S   6 .1          A   .               .               . 68
      O M        S   6 .1          A   .               .               . 68
    90.O M - - -S- -6- 1 - - - - -A- - - - - - - - - - - - - - - - - - 68
      O M        S   6 1           A   .               .               . 68
      O M        S   6 1           A   .               .               . 68
      O M        S   861            A  .               .               .
      O M        S   861            A  .               .               .
      O M        S   86.            A  .               .               . 61
      O M        S   86.            A  .               .               . 61
      O M        S   86.            A  .               .               . 61
      O M        S    6.            A  .               .               . 681
      O M        S    6.            A  .               .               . 681
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      O M        S    6.            A  .               .               . 681
      O M        S    6.            A  .               .               . 681
      O M        S    6.            A  .               .               . 681
      O M        S   16.            A  .               .               . 68
      O M        S   16-            A  .               .               .
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Figure 55.

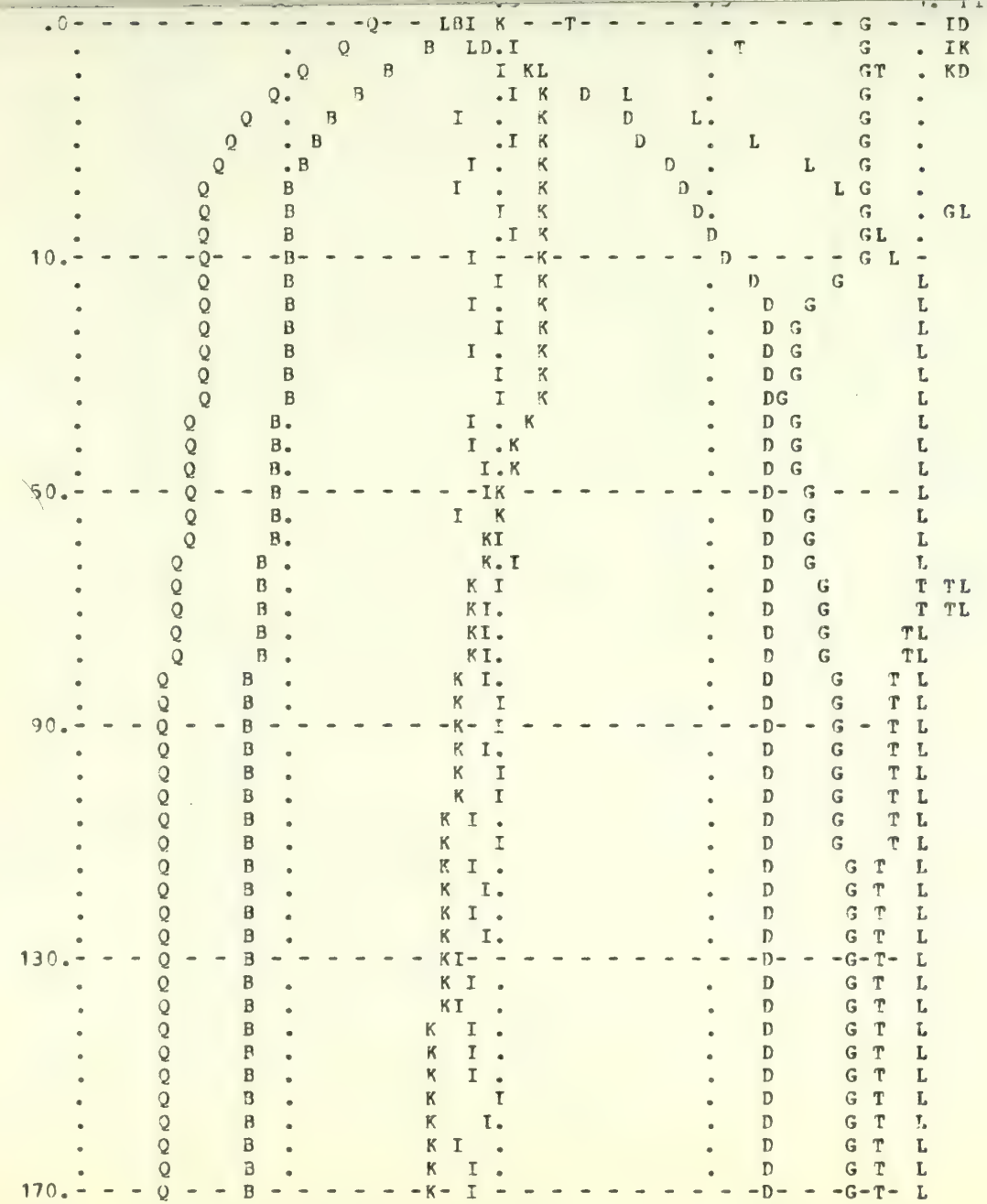


Figure 56.

VIS=V,UGI=U,OVN=O,PIL=P,FLIC=F,DON=N,TWE=W,PWE=E,HAR=H

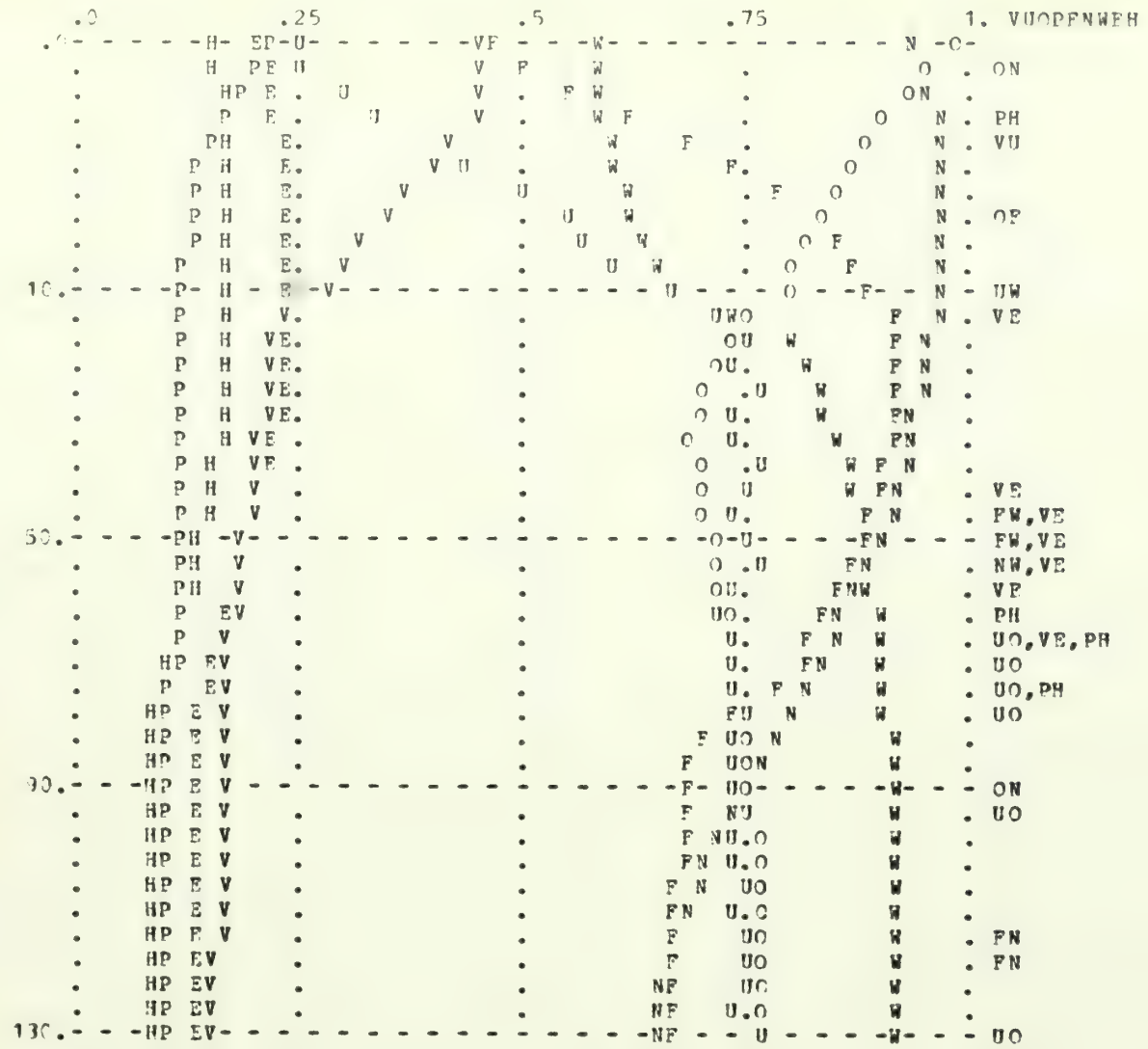


Figure 57.

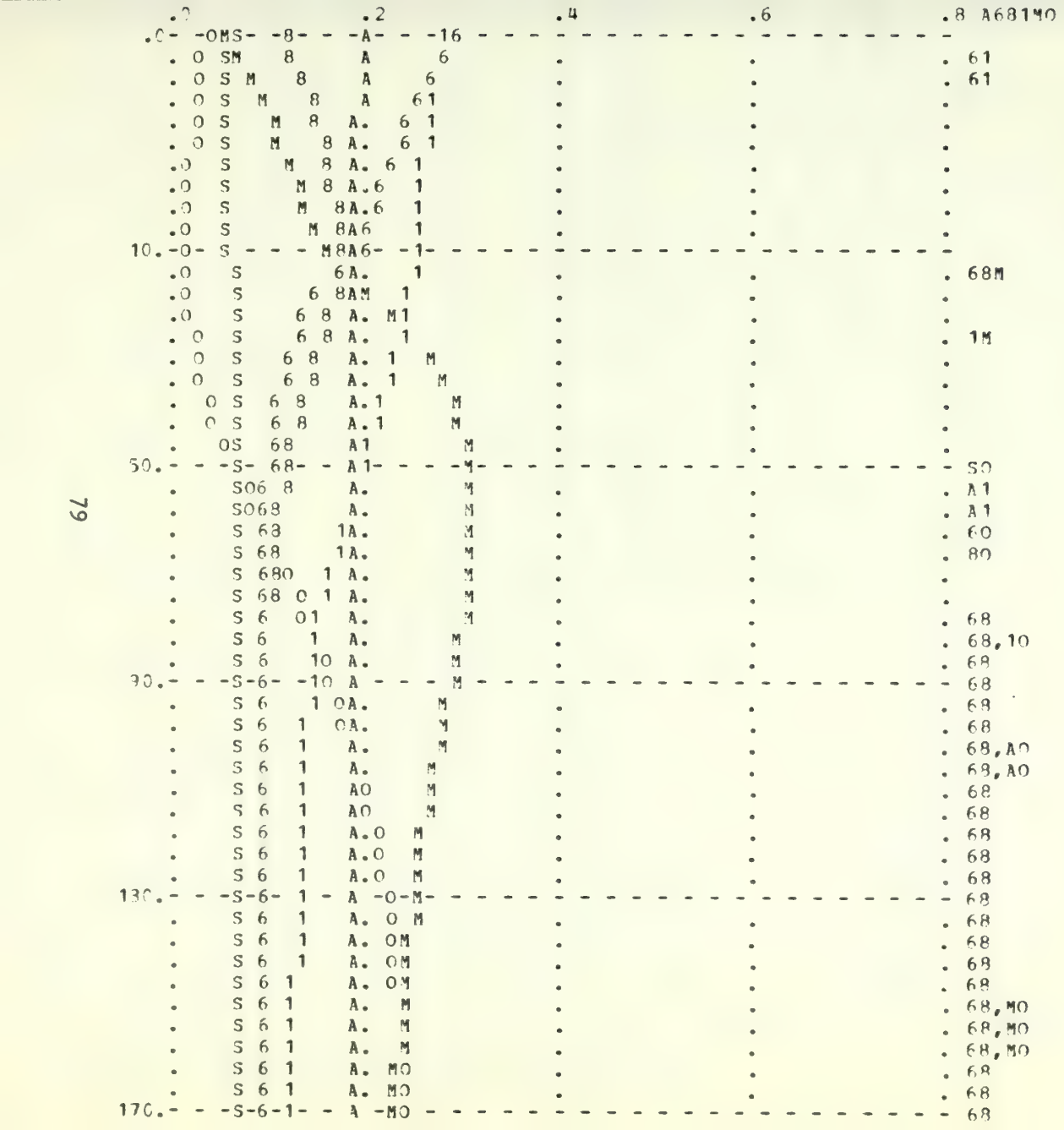
6.4 Mode 160/10: 160-year Rotation and 10-acre Openings (table 7 and figs. 58, 59, 60)

Doubling the rotation period from 80 to 160 years lowers the potential timber index from 0.93 to 0.61 (table 7). At the steady state, trees are removed only from the old-growth stands (fig. 58). Most harvested trees would be relatively large and could be used to support industries requiring large pieces of lumber free of knots. The cubic volume removed annually is about half that removed from a 20-year rotation (0.61 from table 7 divided by 1.4 from table 4) and only one-eighth as much land area would be harvested annually (319.8 acres, table 4, divided by 39.9 acres, table 7).

Indices for all benefits except bluebirds and ovenbirds exceed 0.5 at the steady state (figs. 59 and 60). Ugliness is below 0.5 and sediment is above 0.5. Increasing the size of the openings would reduce the amount of roads and thus the sediment index. But larger openings would reduce the frequency of openings and possibly reduce the value of indices for some animals. These relationships could be determined by examining some intermediate modes.

This mode seems fairly desirable for producing quality sawtimber and related benefits. However, the DYNAST-MB technique of dual rotation periods produced similar benefit indices with greater timber yields (Boyce 1977, sec. 7.3).

TIME	OGS VOG	MTS VMT	P1S VP1	P8S VP8	P6S VP6	SAS VSA	PTI VT	OG MT	P1 P8	P6 SA	SB SEMT	DEPP SQD	TUR GRS	VIS UGL
E+00	E+00 E+03	E+00 E+03	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+03	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00
.0	39.975 95.39	.000 .000	0. 0.	0. 0.	0. 0.	0. 0.	.29592 95.39	225.0 366.0	1808.0 740.0	1843.0 1254.0	200.00 .57349	.51489 .31105	.9112 .93333	.42923 .16736
1.	39.975 126.82	.000 .000	0. 0.	0. 0.	0. 0.	0. 0.	.39341 126.82	212.8 444.3	1769.5 809.7	1763.9 1250.9	194.76 .67376	.45729 .29967	.9455 .93333	.41887 .12201
2.	39.975 153.15	.000 .000	0. 0.	0. 0.	0. 0.	0. 0.	.47509 153.15	196.1 518.7	1737.2 869.9	1689.8 1245.7	178.65 .62648	.42919 .28393	.9774 .93333	.41132 .13205
3.	39.975 168.51	.000 .000	0. 0.	0. 0.	0. 0.	0. 0.	.52273 168.51	177.4 589.4	1710.2 921.5	1620.4 1239.8	177.36 .67765	.42326 .26638	1.0000 .93333	.38739 .11596
4.	39.975 177.44	.000 .000	0. 0.	0. 0.	0. 0.	0. 0.	.55045 177.44	158.3 656.9	1687.7 965.3	1555.3 1234.1	178.47 .52705	.42837 .24849	1.0000 .93333	.36954 .14971
5.	39.975 182.62	.000 .000	0. 0.	0. 0.	0. 0.	0. 0.	.56651 182.62	139.7 721.5	1668.9 1002.1	1494.2 1228.8	180.65 .70376	.43836 .23109	1.0000 .93333	.35461 .11019
6.	39.975 185.60	.000 .000	0. 0.	0. 0.	0. 0.	0. 0.	.57576 185.60	122.2 783.3	1653.4 1032.7	1436.9 1224.3	183.16 .54224	.44992 .21463	1.0000 .93333	.34107 .15156
7.	23.608 183.04	16.367 4.045	0. 0.	0. 0.	0. 0.	0. 0.	.58036 187.08	106.1 842.5	1640.5 1057.6	1383.2 1220.3	185.64 .49894	.46133 .19957	1.0000 .93333	.32834 .15962
8.	24.799 154.00	15.176 32.839	0. 0.	0. 0.	0. 0.	0. 0.	.57961 186.84	96.1 804.8	1629.7 1077.5	1332.9 1217.0	187.92 .64855	.47181 .19013	1.0000 .93333	.31000 .13206
9.	25.975 139.36	14.000 47.820	0. 0.	0. 0.	0. 0.	0. 0.	.58065 187.18	91.3 941.2	1620.6 1093.0	1285.8 1214.2	189.93 .70585	.48102 .18563	1.0000 .93333	.30958 .11518
10.	27.138 133.09	12.837 54.622	0. 0.	0. 0.	0. 0.	0. 0.	.58231 187.71	89.6 983.9	1612.9 1104.4	1241.6 1211.9	191.65 .53903	.48803 .18401	1.0000 .92237	.30214 .15905
50.	39.975 192.24	.000 .000	0. 0.	0. 0.	0. 0.	0. 0.	.59635 192.24	417.2 1978.3	1243.6 753.1	643.9 1199.9	199.87 .60213	.51449 .49136	1.0000 .65584	.23535 .16227
90.	39.975 196.15	.000 .000	0. 0.	0. 0.	0. 0.	0. 0.	.60847 196.15	1052.9 1849.3	913.2 618.3	602.7 1199.4	199.87 .63478	.51450 .76462	1.0000 .59956	.44400 .15089
130.	39.975 197.36	.000 .000	0. 0.	0. 0.	0. 0.	0. 0.	.61225 197.36	1415.1 1599.4	820.6 601.5	599.9 1199.3	199.87 .53483	.51450 .84250	.9448 .59534	.58264 .17316
170.	39.975 197.86	.000 .000	0. 0.	0. 0.	0. 0.	0. 0.	.61377 197.86	1561.5 1472.6	802.9 599.8	599.6 1199.2	199.87 .54790	.51450 .88828	.8991 .59502	.63485 .17113


.0 .2 .4 .6 .8 A681MO
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. 0 S M 8 A 6 . . . 61
. 0 S M 8 A 61 . . .
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. 0 S M 8 A. 6 1 . . .
.0 S M 8 A. 6 1 . . .
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.0 S M 8A.6 1 . . .
.0 S M 8A6 1 . . .
10.-0- S - - - M8A6- -1- - - - - - - - - - - - - - - - - - -
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.0 S 6 8AM 1 . . .
.0 S 6 8 A. M1 . . .
. 0 S 6 8 A. 1 . . . 1M
. 0 S 6 8 A. 1 M . . .
. 0 S 6 8 A. 1 M . . .
. 0 S 6 8 A.1 M . . .
. 0 S 6 8 A.1 M . . .
. OS 68 A1 M . . .
50.- - -S- 68- - A1- - - -M- - - - - - - - - - - - - - - - - - SO
. S06 8 A. M . . . A1
. S068 A. M . . . A1
. S 63 1A. M . . . 60
. S 68 1A. M . . . 80
. S 680 1 A. M . . .
. S 68 0 1 A. M . . .
. S 6 01 A. M . . . 68
. S 6 1 A. M . . . 68,10
. S 6 10 A. M . . . 68
90.- - -S-6- -10 A - - - M - - - - - - - - - - - - - - - - - - 68
. S 6 1 0A. M . . . 68
. S 6 1 0A. M . . . 68
. S 6 1 A. M . . . 68,AO
. S 6 1 A. M . . . 68,AO
. S 6 1 AO M . . . 68
. S 6 1 AO M . . . 68
. S 6 1 A.O M . . . 68
. S 6 1 A.O M . . . 68
. S 6 1 A.O M . . . 68
130.- - -S-6- 1 - A -O-M- - - - - - - - - - - - - - - - - - - 68
. S 6 1 A. O M . . . 68
. S 6 1 A. OM . . . 68
. S 6 1 A. OM . . . 68
. S 6 1 A. OM . . . 68
. S 6 1 A. M . . . 68,MO
. S 6 1 A. M . . . 68,MO
. S 6 1 A. M . . . 68,MO
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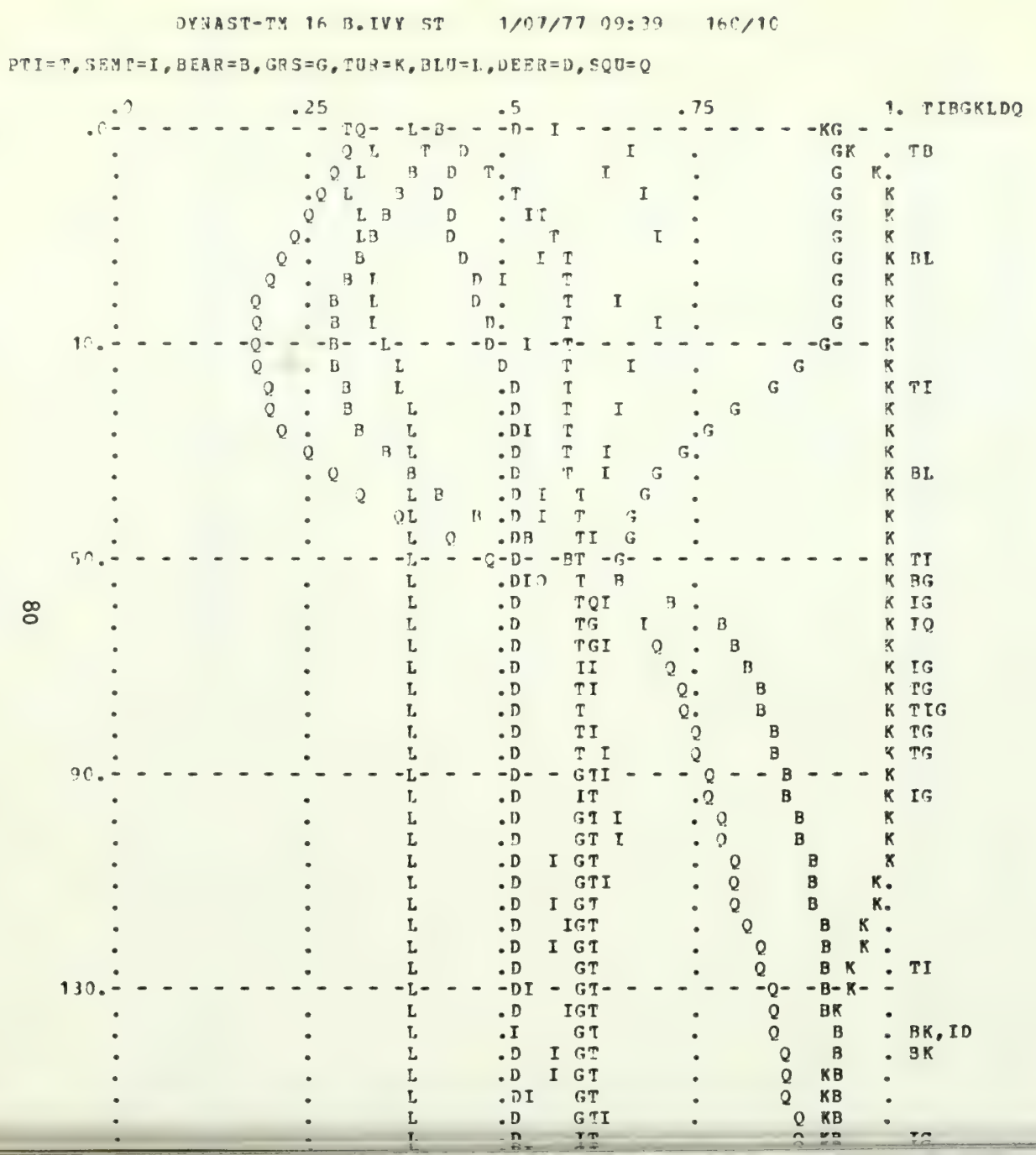
170.- - -S-6-1- - A -MO - - - - - - - - - - - - - - - - - - - 68

Figure 58.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.25
.5
.75
1. TIBGKLDQ
10.
30.
50.
70.
90.
110.
130.

Figure 59.

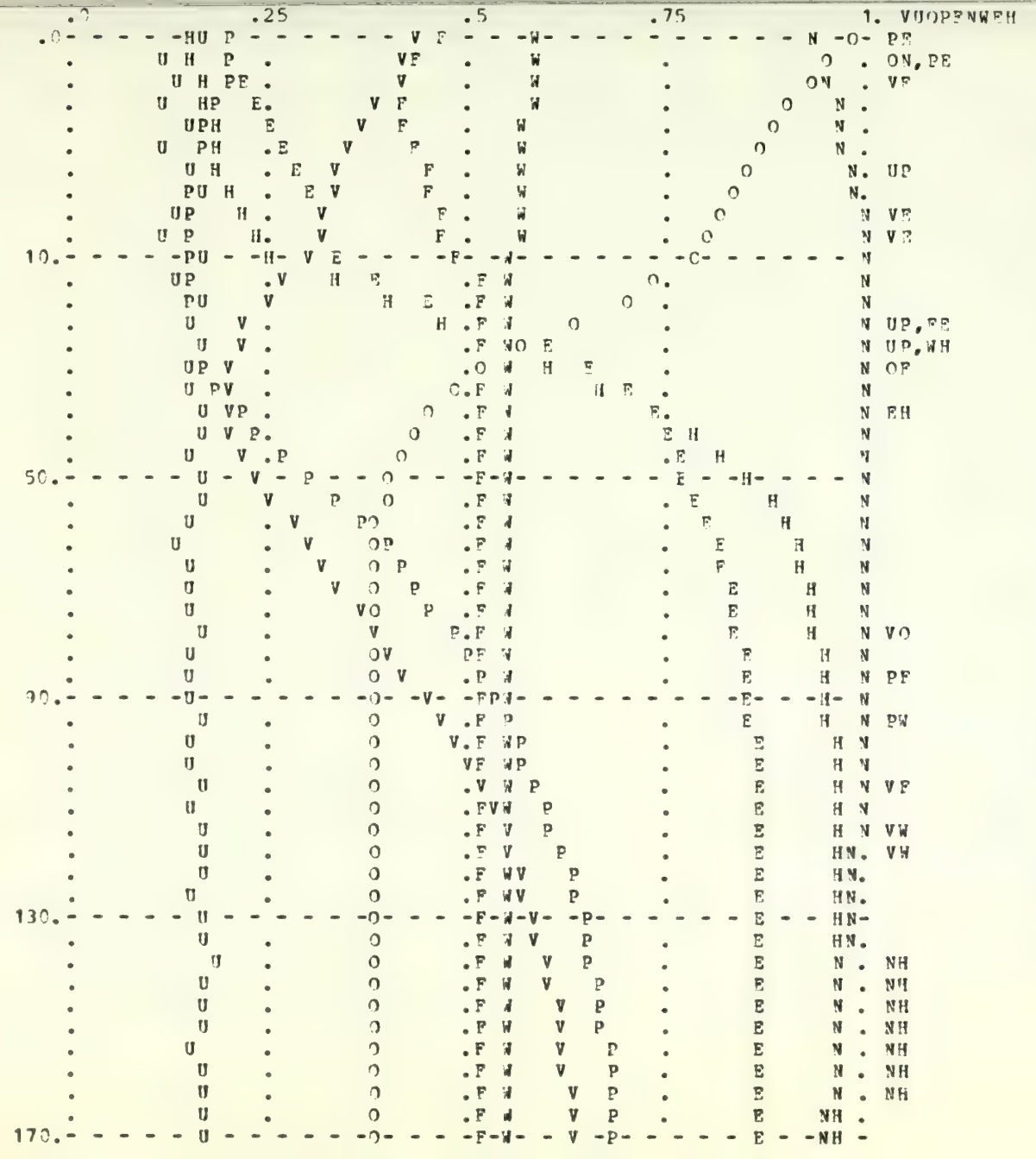

Figure 60.

6.5 Mode 240/5: 240-year Rotation and 5-acre Openings (table 8 and figs. 61, 62, 63)

This long rotation period with relatively small openings probably represents a limit for practical forest management. At this long rotation, much of the harvest would likely be salvage of trees damaged by storms, insects, and diseases. This mode is illustrated as a basis for decisions rather than because it is a practical possibility.

The potential timber index is only 0.4 of the yield under 50-year rotation. All of the harvest would be from old-growth habitats and relatively small areas would be harvested annually (table 8). The proportion of areas in seedling, sapling, and pole habitats is relatively small (fig. 61). This distribution of habitats reduces the habitat indices for a number of animals to less than 0.5 (figs. 62 and 63). Sediment is relatively high because of the large amount of roads required to harvest 5-acre openings. However, increasing the size of openings would reduce the frequency and interspersion of habitats; hence, the wildlife indices would suffer.

TIME	OGS VOG	MTS VMT	P1S VP1	P8S VP8	P6S VP6	SAS VSA	PTI VT	OG MT	P1 P8	P6 SA	SE SEMT	DEFR SOU	TUR GRS	VIS UGL
E+00	E+00 E+03	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+03	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00
.0	26.650 63.83	0. 0.	0. 0.	0. 0.	0. 0.	0. 0.	.19800 63.83	211.6 366.0	1808.0 740.0	1843.0 1254.0	200.00 .71894	.52539 .2985	.54672 .88333	.42392 .10183
1.	26.650 84.87	0. 0.	0. 0.	0. 0.	0. 0.	0. 0.	.26329 84.87	207.3 444.3	1769.5 809.7	1763.9 1250.4	177.43 .78829	.43244 .2945	.56727 .88333	.40084 .06952
2.	26.650 102.52	0. 0.	0. 0.	0. 0.	0. 0.	0. 0.	.31804 102.52	200.6 518.7	1737.2 869.9	1689.8 1243.1	163.33 .75428	.36608 .2882	.58645 .88333	.37636 .07179
3.	26.650 112.84	0. 0.	0. 0.	0. 0.	0. 0.	0. 0.	.35005 112.84	193.4 589.4	1710.2 921.5	1620.2 1233.7	154.26 .79098	.32357 .2814	.60000 .88333	.33998 .05984
4.	26.650 118.87	0. 0.	0. 0.	0. 0.	0. 0.	0. 0.	.36874 118.87	186.5 656.9	1687.7 965.3	1554.9 1223.1	148.32 .69244	.29570 .2750	.60000 .88333	.31247 .07811
5.	26.650 122.38	0. 0.	0. 0.	0. 0.	0. 0.	0. 0.	.37964 122.38	180.6 721.5	1668.9 1002.1	1493.4 1211.8	144.33 .80427	.27697 .2695	.60000 .88333	.29063 .05190
6.	26.650 124.43	0. 0.	0. 0.	0. 0.	0. 0.	0. 0.	.38601 124.43	176.0 783.3	1653.4 1032.6	1435.5 1200.2	141.57 .70129	.26404 .2651	.60000 .88333	.27254 .07279
7.	26.650 125.63	0. 0.	0. 0.	0. 0.	0. 0.	0. 0.	.38973 125.63	172.9 842.7	1640.5 1057.4	1381.1 1188.5	139.62 .67554	.25487 .2621	.60000 .88333	.25703 .07684
8.	26.650 126.33	0. 0.	0. 0.	0. 0.	0. 0.	0. 0.	.39191 126.33	171.2 899.9	1629.7 1077.2	1329.8 1176.8	138.20 .77038	.24820 .2606	.60000 .88333	.24338 .05761
9.	26.650 126.75	0. 0.	0. 0.	0. 0.	0. 0.	0. 0.	.39321 126.75	171.0 954.9	1620.6 1092.4	1281.4 1165.3	137.14 .80495	.24323 .2604	.60000 .88333	.23113 .04897
10.	26.650 127.01	0. 0.	0. 0.	0. 0.	0. 0.	0. 0.	.39400 127.01	172.3 1007.9	1612.8 1103.5	1235.8 1154.0	136.33 .69944	.23946 .2616	.60000 .87136	.21996 .07045
50.	26.650 131.79	0. 0.	0. 0.	0. 0.	0. 0.	0. 0.	.40883 131.79	1006.8 1996.5	1192.1 674.5	526.0 893.3	133.25 .73508	.22500 .7574	.60000 .46145	.20370 .06217
90.	26.650 134.87	0. 0.	0. 0.	0. 0.	0. 0.	0. 0.	.41840 134.87	2113.5 1713.6	750.6 460.8	426.5 824.1	133.25 .76022	.22500 1.0000	.54878 .32408	.24239 .05746
130.	26.650 136.00	0. 0.	0. 0.	0. 0.	0. 0.	0. 0.	.42189 136.00	2762.0 1309.8	591.2 413.8	406.3 805.9	133.25 .69700	.22500 .9238	.41143 .29618	.30809 .06931
170.	26.650 136.48	0. 0.	0. 0.	0. 0.	0. 0.	0. 0.	.42339 136.48	3049.5 1085.9	547.7 403.2	401.4 801.2	133.25 .70455	.22500 .8369	.33321 .28941	.35253 .06790

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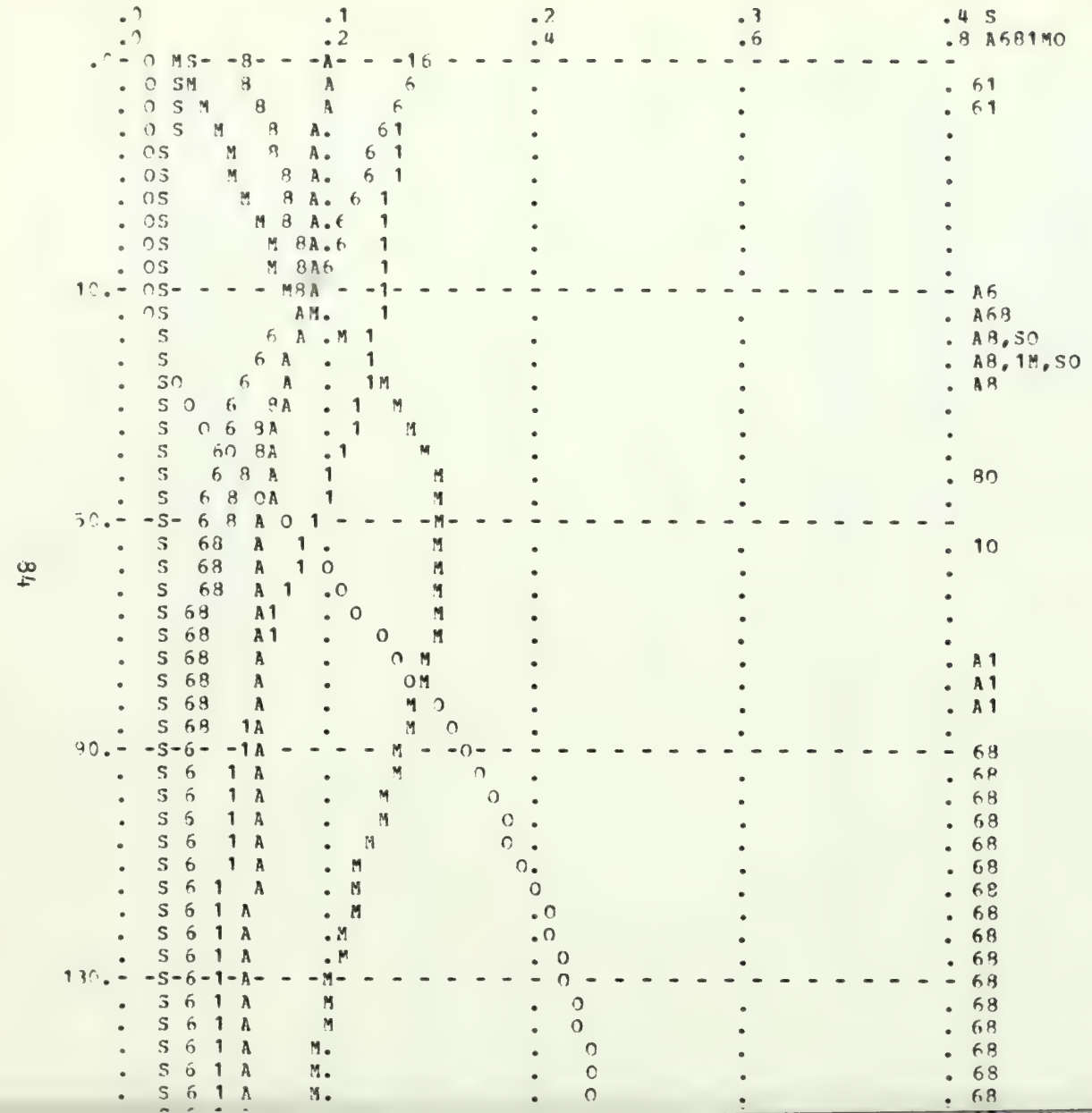
.0 .1 .2 .3 .4 S
.0 .2 .4 .6 .8 A681MO
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. O SM 8 A 6 . . . 61
. O S M 8 A 6 . . . 61
. O S M 8 A. 61 . . .
. OS M 8 A. 6 1 . . .
. OS M 8 A. 6 1 . . .
. OS M 8 A. 6 1 . . .
. OS M 8 A.6 1 . . .
. OS M 8A.6 1 . . .
. OS M 8A6 1 . . .
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. S 6 A . 1 . . . A8,1M,SO
. SO 6 A . 1M . . . A8
. S O 6 8A . 1 M . . .
. S O 6 8A . 1 M . . .
. S 60 8A .1 M . . .
. S 6 8 A 1 M . . . 80
. S 6 8 OA 1 M . . .
30.- -S- 6 8 A O 1 - - - - -M- - - - - - - - - - - - - - - - -
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. S 68 A 1 O M . . .
. S 68 A 1 .O M . . .
. S 68 A1 . O M . . .
. S 68 A1 . O M . . .
. S 68 A . O M . . . A1
. S 68 A . OM . . . A1
. S 68 A . M O . . . A1
. S 68 1A . M O . . .
90.- -S-6- -1A - - - - M - -O- - - - - - - - - - - - - - - - - 68
. S 6 1 A . M O . . . 68
. S 6 1 A . M O . . . 68
. S 6 1 A . M O . . . 68
. S 6 1 A . M O . . . 68
. S 6 1 A . M O. . . . 68
. S 6 1 A . M O . . . 68
. S 6 1 A . M .O . . . 68
. S 6 1 A .M .O . . . 68
. S 6 1 A .M . O . . . 68
130.- -S-6-1-A- - -M- - - - - - - - - O - - - - - - - - - - - - - - - - 68
. S 6 1 A M . O . . . 68
. S 6 1 A M . O . . . 68
. S 6 1 A M. . O . . . 68
. S 6 1 A M. . O . . . 68
. S 6 1 A M. . O . . . 68

Figure 61.

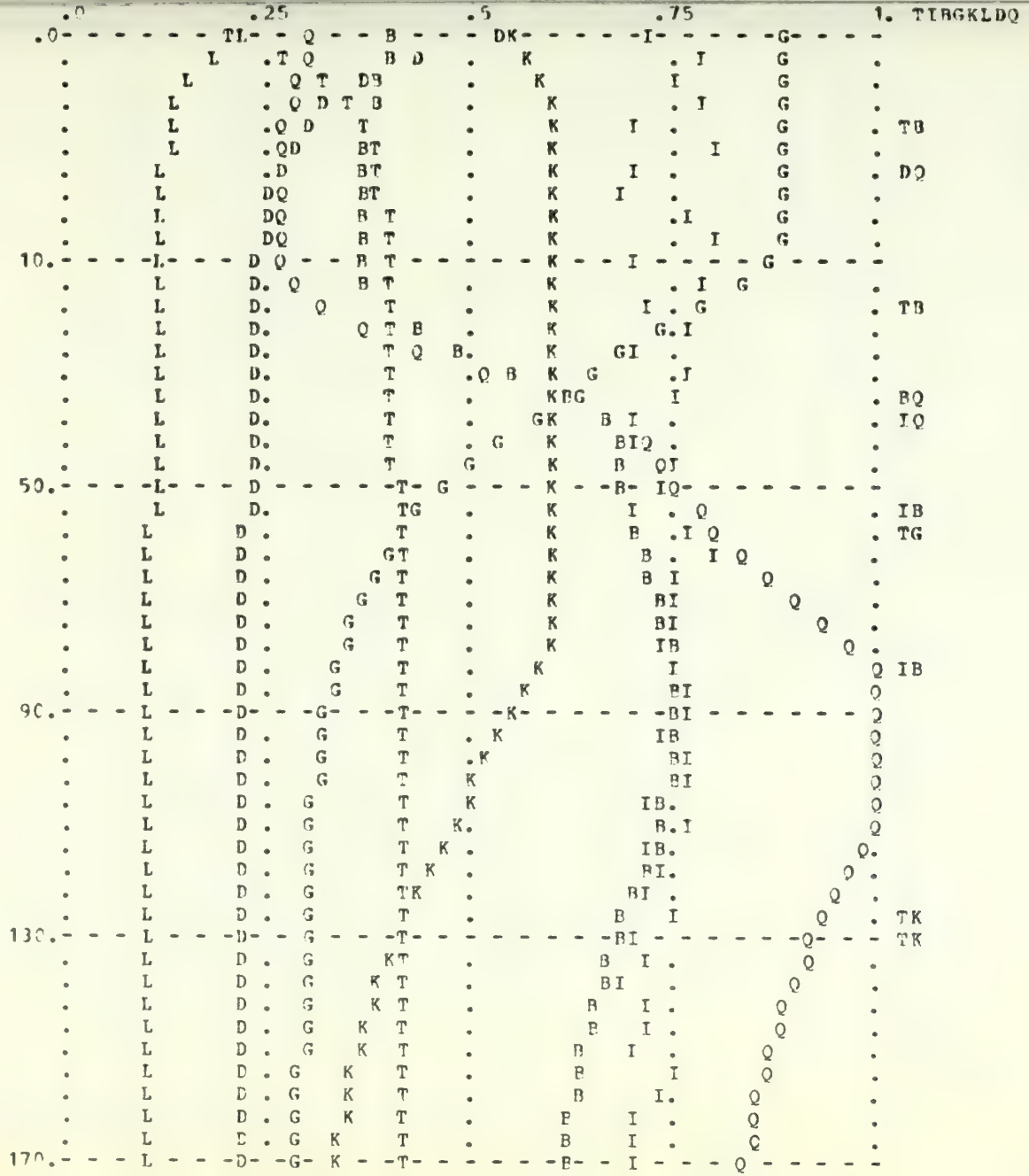

Figure 62.

```
DYNAST-TM 16 B.IVY ST    1/07/77 09:39   240/5

VIS=V,UGL=U,OVN=O,PIL=P,FLIC=F,DON=N,TWE=W,PWE=E,HAR=H

      .0            .25            .5            .75            1. VUOPFNWEH
    .0- - - U H -EP - - -F- - -V- - - - -W- - - - - - - - - - - N -O-
      .   U    H  P  . F      V     .    W         .           O  . ON,PE
      .   U     H PE .F      V      .    W         .          ON  .
      .   U     HP   F    V         .   W          .        O   N . PE
      .    U     P  P.E  V          .   W          .       O    N . PH
      .  U       P  F. V            .  W           .      O     N . VE,PH
      .   U      PH F.V E           .  W           .     O       N.
      .    U     P  FV   E          .  W           .    O        N. PH
      .  U       P F V    E         . W            .   O         N VH
      .  U       P FV. H   E        . W            .  O          N
    10.- - U - - -P-V- - H - E - - - -W- - - - - - - -O- - - - - - N VE
      .  U       V F .        H  E  W             O.             N VP
      .   U    V   P .           W H  E         O  .             N PE
      .  U    V    FP.            W  .    O  E    .             N OH
      .   U    V   F .P          W   .O        H E .             N
      .  U     V   F .   P      W  O .             E H           N
      .  U      V  F .     P  WO     .             .E   H        N
      .   U      V F .       OP      .             .  E    H     N OW
      .   U      V F .      OW  P    .             .   F   H     N
      .   U       VF .     OW     P. .             .     E   H   N
    50.- - U - - - VF- - - O W - - - -P- - - - - - - - - - E - - H N
      .   U        V .   O W         .  P           .       E    HN VE
      .  U         V .  O  W         .    P         .       E    N VE,NH
      .  U         FV.  O W          .       P      .         E  N NH
      .   U        FV. O  W          .         P    .         E  N NH
      .   U        FV. O  W          .           P  .         E  N NH
      .   U        F V O  W          .            P.          E  N NH
      .   U        F V O W           .             .P         E  N NH
      .   U        F VO  W           .             .  P       E  N NH
      .  U         F VO  W           .             .   P      E  N NH
    90.- -U- - - - -F-VO -W- - - - - - - - - - - - - - - - - P - - -E-NH
      .   U        FV.O  W           .             .     P     EN H
      .  U         FV.O  W           .             .     P     EN H
      .  U         F VO  W           .             .      P    N  H NE
      .   U        F VO  W           .             .       P   NE H
      .  U         F OV W            .             .       P  N E H
      .   U        F OV W            .             .        P N E H
      .   U        F O VW            .             .        PN  E H
      .   U        F O  V            .             .         P  E H PN,VW
      .   U        F O  V            .             .        NP  E H VW
    130.- - U - - - -F-O- V - - - - - - - - - - - - - - - - - NP- E H VW
      .   U        F O  WV           .             .       N P  E H
      .   U        F O  WV           .             .      N  P  E H
      .   U        F O  W V          .             .      N  P  E H
      .   U        F O  W V          .             .     N    P E H
      .  U         F O  W V          .             .     N    P E H
      .  U         F O  W V          .             .
```

Figure 63.

6.6 Mode 300/1: 300-year Rotation and 1-acre Openings (table 9, figs. 64, 65, 66)

The desire for "undisturbed" forest has been a source of conflicting objectives in forest management. Debate and decision-making have typically dealt with extreme positions. Analytic procedures in which management concerns itself mainly with choosing between timber and wilderness, optimized or compromised, do not provide satisfactory results for rational decisions. However, the dynamically analytic silviculture technique provides a way to examine rationally a continuum of biologically possible benefits. Mode 300/1 simulates wilderness and other kinds of areas protected from the harvest of timber (fig. 64).

The potential timber index is about 0.3 but these volumes represent natural mortality rather than harvest. Natural mortality would not be as regular as the model indicates, since the unpredictable effects of storms, fire, insects, and diseases would result in irregular rates of mortality. Thus, the potential timber index represents the expected average mortality for these old stands (table 9).

The 1-acre openings represent the most frequent size, since a death of a single large tree may form openings less than 0.5 acre and a "blowdown" may involve many acres (Frothingham, footnote 1). The sediment index, which is related to size of openings, would be at the geologic level (Howell and others 1975) if the dead trees were left undisturbed but would have an unacceptable value of 1 (fig. 65) if the dead trees were removed.

After 170 years, indices for a large number of benefits would be less than 0.5 (figs. 65 and 66). The decline in quality of habitat for many animals is related to the relatively small areas in seedling, sapling, and pole habitats (fig. 64), which provide kinds of food and shelter not available in mature timber and old-growth habitats. The variety of habitats is reduced as the proportion of area in old growth increases.

The decline in indices for bear and squirrel after 90 years is related to the decline in production of hard mast by old-growth trees (U. S. Department of Agriculture, Forest Service 1971). The downy woodpecker index declines because of the decrease in pole timber trees.

Many years, possibly 550, are required for the habitats to come to a steady state, if ever. Irregular rates of mortality and "blowdowns" would probably keep the distribution of habitats oscillating in perpetuity but in a more irregular fashion than illustrated (fig. 64). These old forests favor pileated and hairy woodpeckers and the pewee groups of birds, including the flycatchers (fig. 66).

If the purpose for management is to maintain some proportion of the area in old-growth habitats, the multiple benefit program, DYNAST-MB (Boyce 1977), is more appropriate than DYNAST-TM.

TIME	QGS VQG	MTS VMT	P1S VP1	P8S VP8	P6S VP6	SAS VSA	PTI VT	QG MT	P1 P8	P6 SA	SB SEMT	DEDR SOV	TUR GRS	VIS UGL
E+00	E+00 E+03	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+03	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E-03
.0	21.320 46.37	0. 0.	0. 0.	0. 0.	0. 0.	0. 0.	.14383 46.37	206.3 366.9	1808.0 740.0	1843.0 1254.0	200.00 1.0000	.52539 .2935	.09112 .81667	.42180 .54232
1.	21.320 57.05	0. 0.	0. 0.	0. 0.	0. 0.	0. 0.	.17696 57.05	205.1 444.3	1769.5 809.7	1763.9 1250.2	174.56 1.0000	.41877 .2924	.09455 .81667	.39366 .45487
2.	21.320 71.97	0. 0.	0. 0.	0. 0.	0. 0.	0. 0.	.22327 71.97	202.5 518.7	1737.2 869.9	1689.8 1242.1	157.20 1.0000	.33733 .2899	.09774 .81667	.36236 .40963
3.	21.320 75.63	0. 0.	0. 0.	0. 0.	0. 0.	0. 0.	.23460 75.63	199.8 589.4	1710.2 921.5	1620.2 1231.3	145.03 1.0000	.28023 .2874	.10000 .81667	.32073 .37791
4.	21.320 87.48	0. 0.	0. 0.	0. 0.	0. 0.	0. 0.	.27136 87.48	197.8 656.9	1687.7 965.3	1554.7 1218.7	136.26 1.0000	.23914 .2856	.10000 .81667	.28896 .35508
5.	21.320 80.36	0. 0.	0. 0.	0. 0.	0. 0.	0. 0.	.24929 80.36	197.0 721.5	1668.9 1002.0	1493.1 1205.0	129.80 1.0000	.20883 .2848	.10000 .81667	.26388 .33824
6.	21.320 91.25	0. 0.	0. 0.	0. 0.	0. 0.	0. 0.	.28306 91.25	197.6 783.3	1653.4 1032.5	1435.0 1190.6	124.94 1.0000	.19534 .2853	.10000 .81667	.24150 .32556
7.	21.320 93.32	0. 0.	0. 0.	0. 0.	0. 0.	0. 0.	.28949 93.32	199.6 842.7	1640.5 1057.3	1380.2 1175.8	121.21 1.0000	.18950 .2873	.10000 .81667	.22216 .31584
8.	21.320 87.01	0. 0.	0. 0.	0. 0.	0. 0.	0. 0.	.26992 87.01	203.2 899.9	1629.6 1077.0	1328.5 1160.8	118.30 1.0000	.18497 .2906	.10000 .81667	.20594 .30828
9.	21.320 83.21	0. 0.	0. 0.	0. 0.	0. 0.	0. 0.	.25814 83.21	208.3 954.9	1620.5 1092.1	1279.7 1145.7	116.02 1.0000	.18140 .2954	.10000 .81667	.19204 .30232
10.	21.320 93.36	0. 0.	0. 0.	0. 0.	0. 0.	0. 0.	.28961 93.36	214.9 1007.9	1612.8 1103.2	1233.5 1130.8	114.21 1.0000	.17856 .3016	.10000 .80500	.17990 .29760
50.	21.320 95.90	0. 0.	0. 0.	0. 0.	0. 0.	0. 0.	.29749 95.90	1259.8 1986.5	1171.5 643.1	478.9 770.7	106.60 1.0000	.16667 .7970	.10000 .36642	.16687 .27778
90.	21.320 94.93	0. 0.	0. 0.	0. 0.	0. 0.	0. 0.	.29447 94.93	2543.3 1653.8	685.6 397.8	356.1 674.0	106.60 1.0000	.16667 1.0000	.08559 .20962	.16844 .27778
130.	21.320 101.19	0. 0.	0. 0.	0. 0.	0. 0.	0. 0.	.31391 101.19	3302.6 1192.1	499.4 338.8	328.9 648.6	106.60 1.0000	.16667 .8349	.05523 .17498	.17057 .27778
170.	21.320 101.36	0. 0.	0. 0.	0. 0.	0. 0.	0. 0.	.31443 101.36	3645.3 930.6	445.7 324.6	322.2 641.9	106.60 1.0000	.16667 .6637	.03978 .16634	.19927 .27778

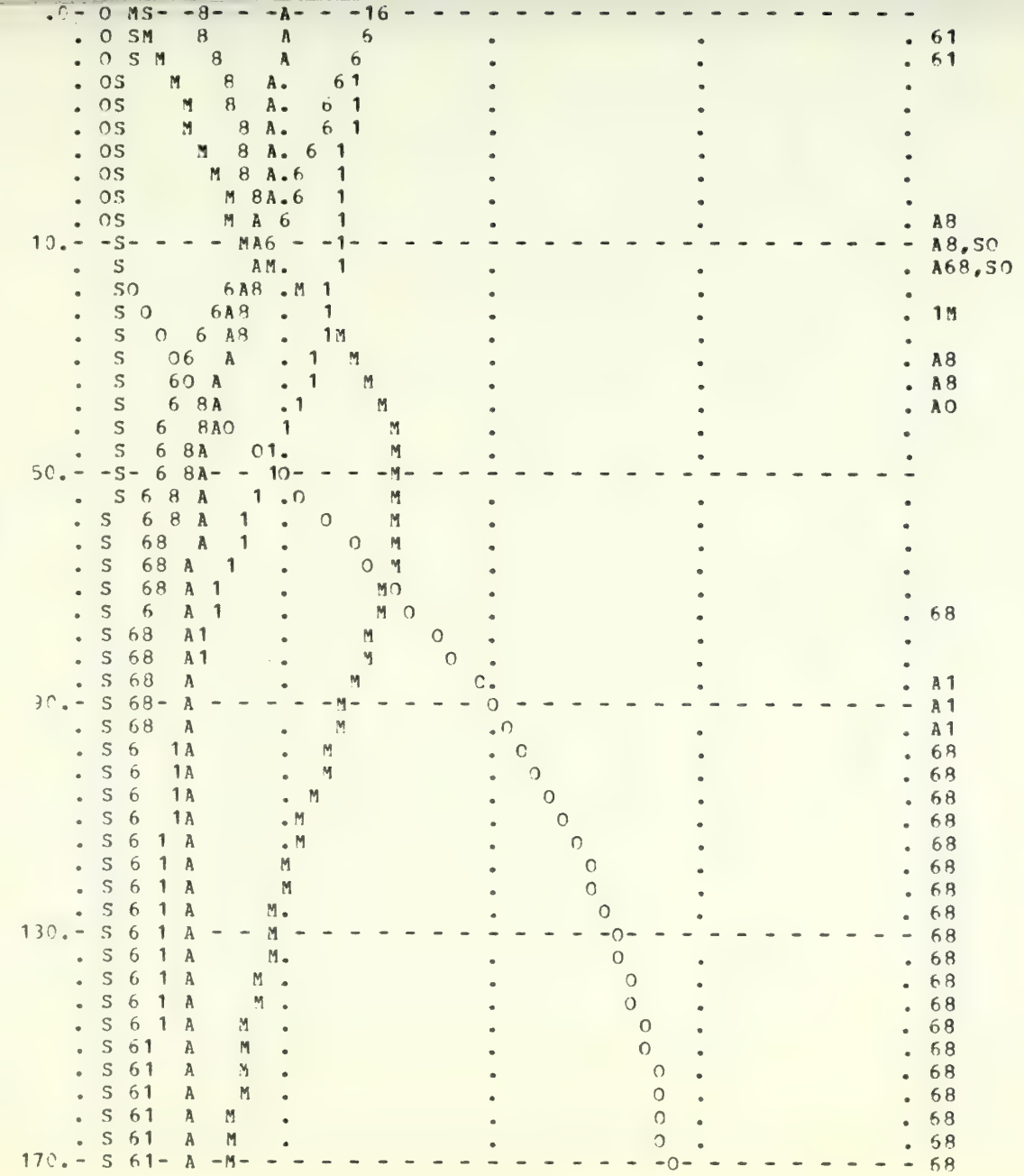

Figure 6.

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      DYNAST-TM 16 B.IVY ST     1/07/77 09:39   300/1

PTI=T,SEMI=I,BEAR=B,GRS=C,TUR=K,BLU=L,DEER=D,SQU=Q

          .0          .25          .5          .75          1. TIBGKLDQ
        .0- -L-K- -T- - - - Q - - B - - - D - - - - - - - -G- - - - - I
          . L   K     T   .   Q     BD    .             .   G         I
          . L   K       T . Q   D   B     .             .   G         I
          . L   K         T.  D     B     .             .   G         I DQ
          .L    K         D.TQ      B     .             .   G         I
          .L    K       D T Q       B     .             .   G         I
          .L    K     D   . T       B     .             .   G         I TQ
          .L    K     D   . T       B     .             .   G         I TQ
          .L    K     D   .TQ       B     .             .   G         I
          .L    K     D   T  Q      B     .             .   G         I
        10.-L- - K - -D- - -TQ - -B- - - - - - - - - - - - G - - - - - I
          .L    K     D     .T    Q   B     .                 .G      I
          .L    K     D     . T       Q B   .               G.        I
          .L    K     D     .T              QB.           G   .       I
          .L    K     D     .  T              . B Q   G     .         I
          .L    K     D     . T               .     P   Q   .         I BG
          .L    K     D     . T               .   G   B     Q .       I
          .L    K     D     .  T              G     B       Q.        I
          .L    K     D     .  T          G   .     B         Q       I
          .L    K     D     . T       G       .     B         .Q      I
        50.-L- - K - D - - - - T - G - - - - - - - -B- - - - - - Q - - - - - I
          .L    K     D     .  T G            .     B       .   Q     I
          .L    K     D     . T G             .     B       .     Q   I
          .L    K     D     . T               .       B     .       Q I TG
          .L    K     D     .G T              .       B     .         Q I
          .L    K     D     G  T              .       B     .           I IQ
          .L    K     D     G  T              .       B     .           I IQ
          .L    K     D   G.   T              .     B       .           I IQ
          .L    K     D  G .   T              .     B       .           I IQ
          .L    K     D  G .   T              .     B       .           I IQ
        90.-L- -K- - D -G- - - T - - - - - - - - - -B- - - - - - - - - - - I IQ
          .L    K     D G   .  T              .   B         .           I IQ
          .L    K     D G   . T               .   B         .           I IQ
          .L    K     D G   . T               .     B       .         Q I
          .L  K       DG    .   T             .   B         .       Q   I
          .L  K       DG    .   I             .  B          .     Q     I
          .L  K       DG    .   T             . B           .   Q       I
          .L  K       DG    .   T             . B           . Q         I
          .L  K       DG    .   T             .B            .Q          I
          .L K        DG    .  T              B             .Q          I
        130.-L-K- - - G - - - -T- - - - - B - - - - - - - - - Q - - - - I GD
          .L K        G     .   T           B.              .  Q        I GD
          .L K        G     .   T         B .               .  Q        I GD
          .L K        G     .   T         B .               . Q         I GD
          .L K        G     .   T       B   .               .Q          I GD
          .L K        G     .   T     B     .               Q           I GD
```

Figure 65.

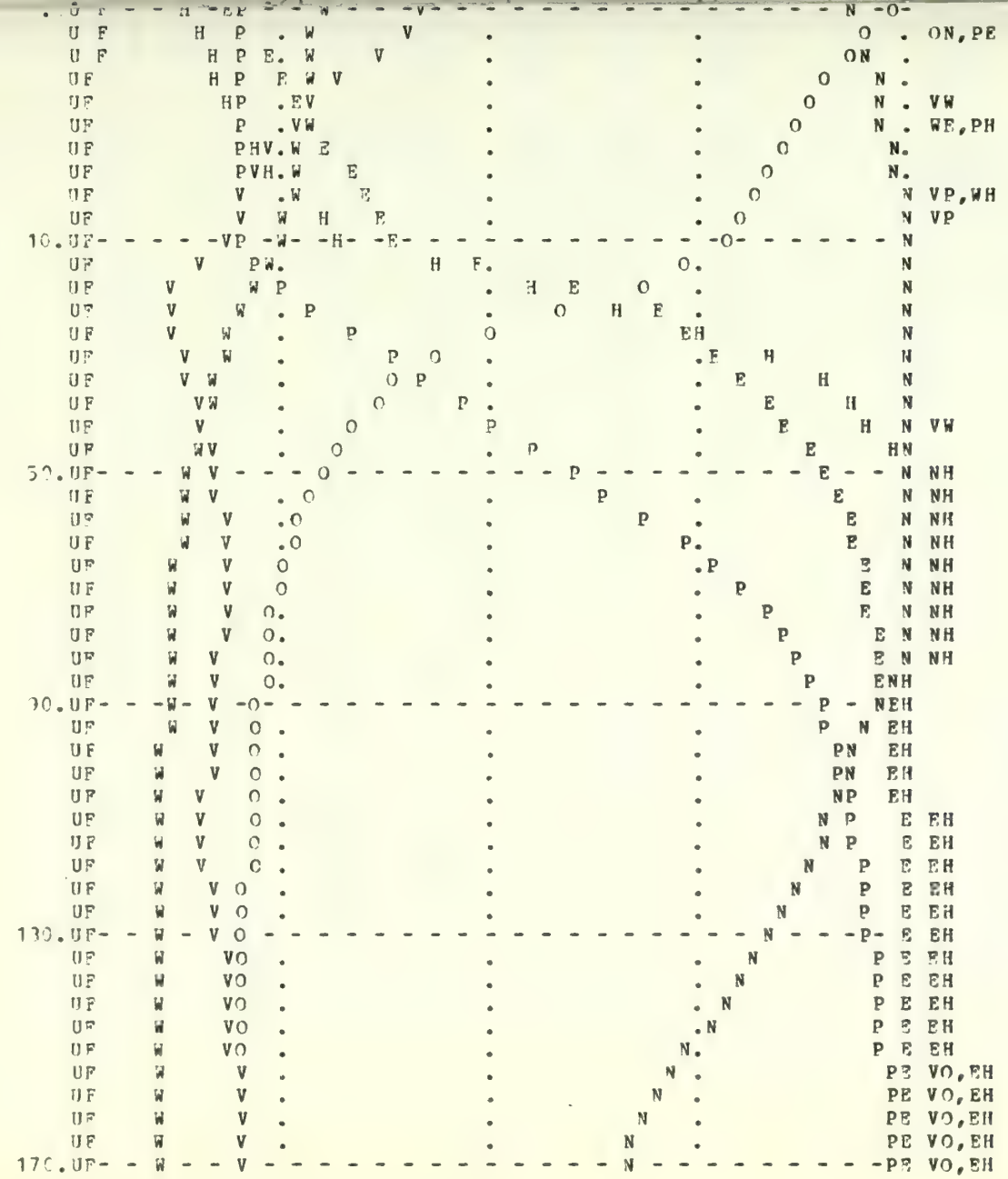

Figure 66.

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APPENDIX A

A LIST OF EQUATIONS WITH DEFINITIONS

For explanations see the text

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ROG.KL=OSA.K/DRT                                          1, R
DRT=2                                                     1.1, C
    ROG     - REMOVE OLD GROWTH (AREA/YEAR)
    OSA     - OLD GROWTH SALES ACCUMULATION (AREA)
    DRT     - DELAY FOR REMOVAL OF TIMBER (YEARS)

OSA.K=OSA.J+DT*(OGS.JK-ROG.JK)                            2, L
OSA=OGS                                                   2.1, N
    OSA     - OLD GROWTH SALES ACCUMULATION (AREA)
    OGS     - OLD GROWTH SALES (AREA/YEAR)
    ROG     - REMOVE OLD GROWTH (AREA/YEAR)

OGS.KL=SFOG.K                                             3, R
    OGS     - OLD GROWTH SALES (AREA/YEAR)
    SFOG    - SALE FRACTION OLD GROWTH (AREA/YEAR)

SFOG.K=FIFGE(LOG.K,MOG.K,COG.K,S)                         4, A
S=3                                                       4.1, C
    SFOG    - SALE FRACTION OLD GROWTH (AREA/YEAR)
    FIFGE   - FIRST IF THIRD GREATER OR EQUAL THE FOURTH
    LOG     - LIQUIDATE OLD GROWTH (AREA/YEAR)
    MOG     - MINIMUM OLD GROWTH SALES (AREA/YEAR)
    COG     - COVERAGE OF OLD GROWTH HABITAT
              (DIMENSIONLESS)
    S       - VARIABLE STANDARD (DIMENSIONLESS)
```

```
MOG.K=IOGS.K*FOG                                                    5, A
FOG=(TAH*OGF)/ROT                                                   5.1, N
TAH=ISE+ISA+IP6+IP8+IP1+IMT+IOG                                     5.2, N
OGF=FIFZE(ST,NS,OGFI)                                               5.3, N
OGFI=(MAX(AOG,ROT))-(MIN((AOG+DOG),ROT))                            5.4, N
ST=1                                                                5.5, C
NS=0                                                                5.6, C
AOG=AMT+DMT                                                         5.7, N
    MOG     - MINIMUM OLD GROWTH SALES (AREA/YEAR)
    IOGS    - INDICATED OLD GROWTH SALES (DIMENSIONLESS)
    FOG     - FLOW OLD GROWTH HABITATS (AREA/YEAR)
    TAH     - TOTAL AREA ALL HABITATS (AREA)
    OGF     - FRACTION REMOVED THROUGH OLD GROWTH HABITAT
                (PERCENT)
    ROT     - ROTATION SELECTED FOR RATE OF HARVEST
                (YEARS)
    ISE     - INVENTORY SEEDLINGS (AREA)
    ISA     - INVENTORY SAPLINGS (AREA)
    IP6     - INVENTORY POLE-6 (AREA)
    IP8     - INVENTORY POLE-8 (AREA)
    IP1     - INVENTORY POLE-10 (AREA)
    IMT     - INVENTORY MATURE TIMBER (AREA)
    IOG     - INVENTORY OLD GROWTH (AREA)
    FIFZE   - FIRST IF THIRD IS ZERO
    ST      - STANDARD VALUE OF 1 (DIMENSIONLESS)
    NS      - NAUGHT STANDARD VALUE (ZERO)
    OGFI    - OLD GROWTH FRACTION INDICATOR (YEARS)
    MAX     - FUNCTION SELECTS MAXIMUM VALUE
    AOG     - TRANSITION AGE OLD GROWTH (YEARS)
    MIN     - FUNCTION SELECTS MINIMUM VALUE
    DOG     - DELAY FOR OLD GROWTH SUCCESSION (YEARS)
    AMT     - TRANSITION AGE MATURE (YEARS)
    DMT     - DELAY FOR MATURE HABITAT SUCCESSION (YEARS)

IOGS.K=TABHL(TIMS,COG.K,.5,1,.1)                                    6, A
TIMS=0/.1/.3/.5/.9/1                                                6.1, T
    IOGS    - INDICATED OLD GROWTH SALES (DIMENSIONLESS)
    TIMS    - TABLE INDICATED TIMBER SALES
    COG     - COVERAGE OF OLD GROWTH HABITAT
                (DIMENSIONLESS)

COG.K=OGR.K/(FOG+E)                                                 7, A
E=.01                                                               7.1, C
    COG     - COVERAGE OF OLD GROWTH HABITAT
                (DIMENSIONLESS)
    OGR     - OLD GROWTH RESERVES (AREA)
    FOG     - FLOW OLD GROWTH HABITATS (AREA/YEAR)
    E       - EQUILIBRIUM CONSTANT (DIMENSION OF
                VARIABLE)
```

```
LOG.K=MIN(OGR.K,FDH)                                    8, A
FDH=TAH/ROT                                             8.1, N
     LOG     - LIQUIDATE OLD GROWTH (AREA/YEAR)
     MIN     - FUNCTION SELECTS MINIMUM VALUE
     OGR     - OLD GROWTH RESERVES (AREA)
     FDH     - FLOW DIVERTED HABITATS (AREA/YEAR)
     TAH     - TOTAL AREA ALL HABITATS (AREA)
     ROT     - ROTATION SELECTED FOR RATE OF HARVEST
               (YEARS)
```

```
RMT.KL=MHA.K/DRT                                              9, R
    RMT     - REMOVE MATURE HABITAT (AREA/YEAR)
    MHA     - MATURE HABITAT SALES ACCUMULATION (AREA)
    DRT     - DELAY FOR REMOVAL OF TIMBER (YEARS)

MHA.K=MHA.J+DT*(MTS.JK-RMT.JK)                                10, L
MHA=MTS                                                       10.1, N
    MHA     - MATURE HABITAT SALES ACCUMULATION (AREA)
    MTS     - MATURE TIMBER SALES (AREA/YEAR)
    RMT     - REMOVE MATURE HABITAT (AREA/YEAR)

MTS.KL=SFMT.K                                                 11, R
    MTS     - MATURE TIMBER SALES (AREA/YEAR)
    SFMT    - SALE FRACTION MATURE HABITAT (AREA/YEAR)

SFMT.K=FIFGE(NS,MTN.K,(SFOG.K+E),FDH)                         12, A
    SFMT    - SALE FRACTION MATURE HABITAT (AREA/YEAR)
    FIFGE   - FIRST IF THIRD GREATER OR EQUAL THE FOURTH
    NS      - NAUGHT STANDARD VALUE (ZERO)
    MTN     - MATURE HABITAT NEEDED (AREA/YEAR)
    SFOG    - SALE FRACTION OLD GROWTH (AREA/YEAR)
    E       - EQUILIBRIUM CONSTANT (DIMENSION OF
              VARIABLE)
    FDH     - FLOW DIVERTED HABITATS (AREA/YEAR)

MTN.K=MIN(MTA.K,(FDH-SFOG.K))                                 13, A
    MTN     - MATURE HABITAT NEEDED (AREA/YEAR)
    MIN     - FUNCTION SELECTS MINIMUM VALUE
    MTA     - MATURE TIMBER AVAILABLE (AREA/YEAR)
    FDH     - FLOW DIVERTED HABITATS (AREA/YEAR)
    SFOG    - SALE FRACTION OLD GROWTH (AREA/YEAR)

MTA.K=FIFGE(LMT.K,MMT.K,CMT.K,S)                              14, A
    MTA     - MATURE TIMBER AVAILABLE (AREA/YEAR)
    FIFGE   - FIRST IF THIRD GREATER OR EQUAL THE FOURTH
    LMT     - LIQUIDATE MATURE HABITAT (AREA/YEAR)
    MMT     - MINIMUM MATURE TIMBER SALES (AREA/YEAR)
    CMT     - COVERAGE OF MATURE HABITAT  (DIMENSIONLESS)
    S       - VARIABLE STANDARD (DIMENSIONLESS)
```

```
MMT.K=IMTS.K*FMT                                          15, A
FMT=(TAH*MTF)/ROT                                         15.1, N
MTF=FIFZE(ST,NS,MTFI)                                     15.2, N
MTFI=(MAX(AMT,ROT))-(MIN(AOG,ROT))                        15.3, N
AMT=AP1+DP1                                               15.4, N
    MMT    - MINIMUM MATURE TIMBER SALES (AREA/YEAR)
    IMTS   - INDICATED MATURE TIMBER SALES
               (DIMENSIONLESS)
    FMT    - FLOW MATURE TIMBER HABITATS (AREA/YEAR)
    TAH    - TOTAL AREA ALL HABITATS (AREA)
    MTF    - FRACTION REMOVED THROUGH MATURE HABITAT
               (PERCENT)
    ROT    - ROTATION SELECTED FOR RATE OF HARVEST
               (YEARS)
    FIFZE  - FIRST IF THIRD IS ZERO
    ST     - STANDARD VALUE OF 1 (DIMENSIONLESS)
    NS     - NAUGHT STANDARD VALUE (ZERO)
    MTFI   - MATURE TIMBER FRACTION INDICATOR (YEARS)
    MAX    - FUNCTION SELECTS MAXIMUM VALUE
    AMT    - TRANSITION AGE MATURE (YEARS)
    MIN    - FUNCTION SELECTS MINIMUM VALUE
    AOG    - TRANSITION AGE OLD GROWTH (YEARS)
    AP1    - TRANSITION AGE POLE-10 (YEARS)
    DP1    - DELAY FOR POLE-10 SUCCESSION (YEARS)

IMTS.K=TABHL(TIMS,CMT.K,.5,1,.1)                          16, A
    IMTS   - INDICATED MATURE TIMBER SALES
               (DIMENSIONLESS)
    TIMS   - TABLE INDICATED TIMBER SALES
    CMT    - COVERAGE OF MATURE HABITAT  (DIMENSIONLESS)

CMT.K=MTR.K/(FMT+E)                                       17, A
    CMT    - COVERAGE OF MATURE HABITAT  (DIMENSIONLESS)
    MTR    - MATURE TIMBER RESERVES (AREA)
    FMT    - FLOW MATURE TIMBER HABITATS (AREA/YEAR)
    E      - EQUILIBRIUM CONSTANT (DIMENSION OF
               VARIABLE)

LMT.K=MIN(MTR.K,FDH)                                      18, A
    LMT    - LIQUIDATE MATURE HABITAT (AREA/YEAR)
    MIN    - FUNCTION SELECTS MINIMUM VALUE
    MTR    - MATURE TIMBER RESERVES (AREA)
    FDH    - FLOW DIVERTED HABITATS (AREA/YEAR)
```

```
RP1.KL=P1SA.K/DRT                                          19, R
    RP1    - REMOVE POLE-10 HABITAT (AREA/YEAR)
    P1SA   - POLE-10 SALES ACCUMULATION (AREA)
    DRT    - DELAY FOR REMOVAL OF TIMBER (YEARS)

P1SA.K=P1SA.J+DT*(P1S.JK-RP1.JK)                           20, L
P1SA=P1S                                                   20.1, N
    P1SA   - POLE-10 SALES ACCUMULATION (AREA)
    P1S    - POLE-10 SALES (AREA/YEAR)
    RP1    - REMOVE POLE-10 HABITAT (AREA/YEAR)

P1S.KL=SFP1.K                                              21, R
    P1S    - POLE-10 SALES (AREA/YEAR)
    SFP1   - SALE FRACTION POLE-10 HABITAT (AREA/YEAR)

SFP1.K=FIFGE(NS,P1N.K,(SOM.K+E),FDH)                       22, A
    SFP1   - SALE FRACTION POLE-10 HABITAT (AREA/YEAR)
    FIFGE  - FIRST IF THIRD GREATER OR EQUAL THE FOURTH
    NS     - NAUGHT STANDARD VALUE (ZERO)
    P1N    - POLE-10 HABITAT NEEDED (AREA/YEAR)
    SOM    - SALE OLD GROWTH + MATURE (AREA/YEAR)
    E      - EQUILIBRIUM CONSTANT (DIMENSION OF
               VARIABLE)
    FDH    - FLOW DIVERTED HABITATS (AREA/YEAR)

SOM.K=SFOG.K+SFMT.K                                        23, A
    SOM    - SALE OLD GROWTH + MATURE (AREA/YEAR)
    SFOG   - SALE FRACTION OLD GROWTH (AREA/YEAR)
    SFMT   - SALE FRACTION MATURE HABITAT (AREA/YEAR)

P1N.K=MIN(P1A.K,(FDH-SOM.K))                               24, A
    P1N    - POLE-10 HABITAT NEEDED (AREA/YEAR)
    MIN    - FUNCTION SELECTS MINIMUM VALUE
    P1A    - POLE-10 AVAILABLE (AREA/YEAR)
    FDH    - FLOW DIVERTED HABITATS (AREA/YEAR)
    SOM    - SALE OLD GROWTH + MATURE (AREA/YEAR)

P1A.K=FIFGE(LP1.K,MP1.K,CP1.K,S)                           25, A
    P1A    - POLE-10 AVAILABLE (AREA/YEAR)
    FIFGE  - FIRST IF THIRD GREATER OR EQUAL THE FOURTH
    LP1    - LIQUIDATE POLE-10 (AREA/YEAR)
    MP1    - MINIMUM POLE-10 SALES (AREA/YEAR)
    CP1    - COVERAGE OF POLE-10 HABITAT (DIMENSIONLESS)
    S      - VARIABLE STANDARD (DIMENSIONLESS)
```

```
MP1.K=IP1S.K*FP1                                              26, A
FP1=(TAH*P1F)/ROT                                             26.1, N
P1F=FIFZE(ST,NS,P1FI)                                         26.2, N
P1FI=(MAX(AP1,ROT))-(MIN(AMT,ROT))                            26.3, N
AP1=AP8+DP8                                                   26.4, N
     MP1     - MINIMUM POLE-10 SALES (AREA/YEAR)
     IP1S    - INDICATED POLE-10 SALES (DIMENSIONLESS)
     FP1     - FLOW POLE-10 HABITATS (AREA/YEAR)
     TAH     - TOTAL AREA ALL HABITATS (AREA)
     P1F     - FRACTION REMOVED THROUGH POLE-10 HABITAT
                 (PERCENT)
     ROT     - ROTATION SELECTED FOR RATE OF HARVEST
                 (YEARS)
     FIFZE   - FIRST IF THIRD IS ZERO
     ST      - STANDARD VALUE OF 1 (DIMENSIONLESS)
     NS      - NAUGHT STANDARD VALUE (ZERO)
     P1FI    - POLE-10 FRACTION INDICATOR (YEARS)
     MAX     - FUNCTION SELECTS MAXIMUM VALUE
     AP1     - TRANSITION AGE POLE-10 (YEARS)
     MIN     - FUNCTION SELECTS MINIMUM VALUE
     AMT     - TRANSITION AGE MATURE (YEARS)
     AP8     - TRANSITION AGE POLE-8 (YEARS)
     DP8     - DELAY FOR POLE-8 SUCCESSION (YEARS)

IP1S.K=TABHL(TIMS,CP1.K,.5,1,.1)                              27, A
     IP1S    - INDICATED POLE-10 SALES (DIMENSIONLESS)
     TIMS    - TABLE INDICATED TIMBER SALES
     CP1     - COVERAGE OF POLE-10 HABITAT (DIMENSIONLESS)

CP1.K=P1R.K/(FP1+E)                                           28, A
     CP1     - COVERAGE OF POLE-10 HABITAT (DIMENSIONLESS)
     P1R     - POLE-10 RESERVES (AREA)
     FP1     - FLOW POLE-10 HABITATS (AREA/YEAR)
     E       - EQUILIBRIUM CONSTANT (DIMENSION OF
                 VARIABLE)

LP1.K=MIN(P1R.K,FDH)                                          29, A
     LP1     - LIQUIDATE POLE-10 (AREA/YEAR)
     MIN     - FUNCTION SELECTS MINIMUM VALUE
     P1R     - POLE-10 RESERVES (AREA)
     FDH     - FLOW DIVERTED HABITATS (AREA/YEAR)
```

```
RP8.KL=P8SA.K/DRT                                          30, R
    RP8    - REMOVE POLE-8 HABITAT (AREA/YEAR)
    P8SA   - POLE-8 SALES ACCUMULATION (AREA)
    DRT    - DELAY FOR REMOVAL OF TIMBER (YEARS)

P8SA.K=P8SA.J+DT*(P8S.JK-RP8.JK)                           31, L
P8SA=P8S                                                   31.1, N
    P8SA   - POLE-8 SALES ACCUMULATION (AREA)
    P8S    - POLE-8 SALES (AREA/YEAR)
    RP8    - REMOVE POLE-8 HABITAT (AREA/YEAR)

P8S.KL=SFP8.K                                              32, R
    P8S    - POLE-8 SALES (AREA/YEAR)
    SFP8   - SALE FRACTION POLE-8 HABITAT (AREA/YEAR)

SFP8.K=FIFGE(NS,P8N.K,(SOM1.K+E),FDH)                      33, A
    SFP8   - SALE FRACTION POLE-8 HABITAT (AREA/YEAR)
    FIFGE  - FIRST IF THIRD GREATER OR EQUAL THE FOURTH
    NS     - NAUGHT STANDARD VALUE (ZERO)
    P8N    - POLE-8 HABITAT NEEDED (AREA/YEAR)
    SOM1   - SALE OLD GROWTH + MATURE + POLE-10 (AREA/
               YEAR)
    E      - EQUILIBRIUM CONSTANT (DIMENSION OF
               VARIABLE)
    FDH    - FLOW DIVERTED HABITATS (AREA/YEAR)

SOM1.K=SOM.K+SFP1.K                                        34, A
    SOM1   - SALE OLD GROWTH + MATURE + POLE-10 (AREA/
               YEAR)
    SOM    - SALE OLD GROWTH + MATURE (AREA/YEAR)
    SFP1   - SALE FRACTION POLE-10 HABITAT (AREA/YEAR)

P8N.K=MIN(P8A.K,(FDH-SOM1.K))                              35, A
    P8N    - POLE-8 HABITAT NEEDED (AREA/YEAR)
    MIN    - FUNCTION SELECTS MINIMUM VALUE
    P8A    - POLE-8 AVAILABLE (AREA/YEAR)
    FDH    - FLOW DIVERTED HABITATS (AREA/YEAR)
    SOM1   - SALE OLD GROWTH + MATURE + POLE-10 (AREA/
               YEAR)

P8A.K=FIFGE(LP8.K,MP8.K,CP8.K,S)                           36, A
    P8A    - POLE-8 AVAILABLE (AREA/YEAR)
    FIFGE  - FIRST IF THIRD GREATER OR EQUAL THE FOURTH
    LP8    - LIQUIDATE POLE-8 (AREA/YEAR)
    MP8    - MINIMUM POLE-8 SALES (AREA/YEAR)
    CP8    - COVERAGE OF POLE-8  HABITAT (DIMENSIONLESS)
    S      - VARIABLE STANDARD (DIMENSIONLESS)
```

```
MP8.K=IP8S.K*FP8                                              37, A
FP8=(TAH*P8F)/ROT                                             37.1, N
P8F=FIFZE(ST,NS,P8FI)                                         37.2, N
P8FI=(MAX(AP8,ROT))-(MIN(AP1,ROT))                            37.3, N
AP8=AP6+DP6                                                   37.4, N
     MP8     - MINIMUM POLE-8 SALES (AREA/YEAR)
     IP8S    - INDICATED POLE-8 SALES (DIMENSIONLESS)
     FP8     - FLOW POLE-8 HABITATS (AREA/YEAR)
     TAH     - TOTAL AREA ALL HABITATS (AREA)
     P8F     - FRACTION REMOVED THROUGH POLE-8 HABITAT
               (PERCENT)
     ROT     - ROTATION SELECTED FOR RATE OF HARVEST
               (YEARS)
     FIFZE   - FIRST IF THIRD IS ZERO
     ST      - STANDARD VALUE OF 1 (DIMENSIONLESS)
     NS      - NAUGHT STANDARD VALUE (ZERO)
     P8FI    - POLE-8 FRACTION INDICATOR (YEARS)
     MAX     - FUNCTION SELECTS MAXIMUM VALUE
     AP8     - TRANSITION AGE POLE-8 (YEARS)
     MIN     - FUNCTION SELECTS MINIMUM VALUE
     AP1     - TRANSITION AGE POLE-10 (YEARS)
     AP6     - TRANSITION AGE POLE-6 (YEARS)
     DP6     - DELAY FOR POLE-6 SUCCESSION (YEARS)

IP8S.K=TABHL(TIMS,CP8.K,.5,1,.1)                              38, A
     IP8S    - INDICATED POLE-8 SALES (DIMENSIONLESS)
     TIMS    - TABLE INDICATED TIMBER SALES
     CP8     - COVERAGE OF POLE-8  HABITAT (DIMENSIONLESS)

CP8.K=P8R.K/(FP8+E)                                           39, A
     CP8     - COVERAGE OF POLE-8  HABITAT (DIMENSIONLESS)
     P8R     - POLE-8 RESERVES (AREA)
     FP8     - FLOW POLE-8 HABITATS (AREA/YEAR)
     E       - EQUILIBRIUM CONSTANT (DIMENSION OF
               VARIABLE)

LP8.K=MIN(P8R.K,FDH)                                          40, A
     LP8     - LIQUIDATE POLE-8 (AREA/YEAR)
     MIN     - FUNCTION SELECTS MINIMUM VALUE
     P8R     - POLE-8 RESERVES (AREA)
     FDH     - FLOW DIVERTED HABITATS (AREA/YEAR)
```

```
RP6.KL=P6SA.K/DRT                                          41, R
    RP6    - REMOVE POLE-6 HABITAT (AREA/YEAR)
    P6SA   - POLE-6 SALES ACCUMULATION (AREA)
    DRT    - DELAY FOR REMOVAL OF TIMBER (YEARS)

P6SA.K=P6SA.J+DT*(P6S.JK-RP6.JK)                           42, L
P6SA=P6S                                                   42.1, N
    P6SA   - POLE-6 SALES ACCUMULATION (AREA)
    P6S    - POLE-6 SALES (AREA/YEAR)
    RP6    - REMOVE POLE-6 HABITAT (AREA/YEAR)

P6S.KL=SFP6.K                                              43, R
    P6S    - POLE-6 SALES (AREA/YEAR)
    SFP6   - SALE FRACTION POLE-6 HABITAT (AREA/YEAR)

SFP6.K=FIFGE(NS,P6N.K,(SOM8.K+E),FDH)                      44, A
    SFP6   - SALE FRACTION POLE-6 HABITAT (AREA/YEAR)
    FIFGE  - FIRST IF THIRD GREATER OR EQUAL THE FOURTH
    NS     - NAUGHT STANDARD VALUE (ZERO)
    P6N    - POLE-6 HABITAT NEEDED (AREA/YEAR)
    SOM8   - SALE OLD GROWTH + MATURE + POLE-10 + POLE-8
               (AREA/YEAR)
    E      - EQUILIBRIUM CONSTANT (DIMENSION OF
               VARIABLE)
    FDH    - FLOW DIVERTED HABITATS (AREA/YEAR)

SOM8.K=SOM1.K+SFP8.K                                       45, A
    SOM8   - SALE OLD GROWTH + MATURE + POLE-10 + POLE-8
               (AREA/YEAR)
    SOM1   - SALE OLD GROWTH + MATURE + POLE-10 (AREA/
               YEAR)
    SFP8   - SALE FRACTION POLE-8 HABITAT (AREA/YEAR)

P6N.K=MIN(P6A.K,(FDH-SOM8.K))                              46, A
    P6N    - POLE-6 HABITAT NEEDED (AREA/YEAR)
    MIN    - FUNCTION SELECTS MINIMUM VALUE
    P6A    - POLE-6 AVAILABLE (AREA/YEAR)
    FDH    - FLOW DIVERTED HABITATS (AREA/YEAR)
    SOM8   - SALE OLD GROWTH + MATURE + POLE-10 + POLE-8
               (AREA/YEAR)

P6A.K=FIFGE(LP6.K,MP6.K,CP6.K,S)                           47, A
    P6A    - POLE-6 AVAILABLE (AREA/YEAR)
    FIFGE  - FIRST IF THIRD GREATER OR EQUAL THE FOURTH
    LP6    - LIQUIDATE POLE-6 (AREA/YEAR)
    MP6    - MINIMUM POLE-6 SALES (AREA/YEAR)
    CP6    - COVERAGE OF POLE-6  HABITAT (DIMENSIONLESS)
    S      - VARIABLE STANDARD (DIMENSIONLESS)
```

```
MP6.K=IP6S.K*FP6                                          48, A
FP6=(TAH*P6F)/ROT                                         48.1, N
P6F=FIFZE(ST,NS,P6FI)                                     48.2, N
P6FI=(MAX(AP6,ROT))-(MIN(AP8,ROT))                        48.3, N
AP6=ASA+DSA                                               48.4, N
    MP6     - MINIMUM POLE-6 SALES (AREA/YEAR)
    IP6S    - INDICATED POLE-6 SALES (DIMENSIONLESS)
    FP6     - FLOW POLE-6 HABITATS (AREA/YEAR)
    TAH     - TOTAL AREA ALL HABITATS (AREA)
    P6F     - FRACTION REMOVED THROUGH POLE-6 HABITAT
              (PERCENT)
    ROT     - ROTATION SELECTED FOR RATE OF HARVEST
              (YEARS)
    FIFZE   - FIRST IF THIRD IS ZERO
    ST      - STANDARD VALUE OF 1 (DIMENSIONLESS)
    NS      - NAUGHT STANDARD VALUE (ZERO)
    P6FI    - POLE-6 FRACTION INDICATOR (YEARS)
    MAX     - FUNCTION SELECTS MAXIMUM VALUE
    AP6     - TRANSITION AGE POLE-6 (YEARS)
    MIN     - FUNCTION SELECTS MINIMUM VALUE
    AP8     - TRANSITION AGE POLE-8 (YEARS)
    ASA     - TRANSITION AGE SAPLINGS (YEARS)
    DSA     - DELAY FOR SAPLING SUCCESSION (YEARS)

IP6S.K=TABHL(TIMS,CP6.K,.5,1,.1)                          49, A
    IP6S    - INDICATED POLE-6 SALES (DIMENSIONLESS)
    TIMS    - TABLE INDICATED TIMBER SALES
    CP6     - COVERAGE OF POLE-6  HABITAT (DIMENSIONLESS)

CP6.K=P6R.K/(FP6+E)                                       50, A
    CP6     - COVERAGE OF POLE-6  HABITAT (DIMENSIONLESS)
    P6R     - POLE-6 RESERVES (AREA)
    FP6     - FLOW POLE-6 HABITATS (AREA/YEAR)
    E       - EQUILIBRIUM CONSTANT (DIMENSION OF
              VARIABLE)

LP6.K=MIN(P6R.K,FDH)                                      51, A
    LP6     - LIQUIDATE POLE-6 (AREA/YEAR)
    MIN     - FUNCTION SELECTS MINIMUM VALUE
    P6R     - POLE-6 RESERVES (AREA)
    FDH     - FLOW DIVERTED HABITATS (AREA/YEAR)
```

```
RSA.KL=SASA.K/DRT                                          52, R
    RSA    - REMOVE SAPLINGS HABITAT (AREA/YEAR)
    SASA   - SAPLING SALES ACCUMULATION (AREA)
    DRT    - DELAY FOR REMOVAL OF TIMBER (YEARS)

SASA.K=SASA.J+DT*(SAS.JK-RSA.JK)                           53, L
SASA=SAS                                                   53.1, N
    SASA   - SAPLING SALES ACCUMULATION (AREA)
    SAS    - SAPLING SALES (AREA/YEAR)
    RSA    - REMOVE SAPLINGS HABITAT (AREA/YEAR)

SAS.KL=SFSA.K                                              54, R
    SAS    - SAPLING SALES (AREA/YEAR)
    SFSA   - SALE FRACTION SAPLING HABITAT (AREA/YEAR)

SFSA.K=FIFGE(NS,SAN.K,(SOM6.K+E),FDH)                      55, A
    SFSA   - SALE FRACTION SAPLING HABITAT (AREA/YEAR)
    FIFGE  - FIRST IF THIRD GREATER OR EQUAL THE FOURTH
    NS     - NAUGHT STANDARD VALUE (ZERO)
    SAN    - SAPLING HABITAT NEEDED (AREA/YEAR)
    SOM6   - SALE OLD GROWTH + MATURE + POLE-10 + POLE-8
               + POLE-6 (AREA/YEAR)
    E      - EQUILIBRIUM CONSTANT (DIMENSION OF
               VARIABLE)
    FDH    - FLOW DIVERTED HABITATS (AREA/YEAR)

SOM6.K=SOM8.K+SFP6.K                                       56, A
    SOM6   - SALE OLD GROWTH + MATURE + POLE-10 + POLE-8
               + POLE-6 (AREA/YEAR)
    SOM8   - SALE OLD GROWTH + MATURE + POLE-10 + POLE-8
               (AREA/YEAR)
    SFP6   - SALE FRACTION POLE-6 HABITAT (AREA/YEAR)

SAN.K=MIN(SAA.K,(FDH-SOM6.K))                              57, A
    SAN    - SAPLING HABITAT NEEDED (AREA/YEAR)
    MIN    - FUNCTION SELECTS MINIMUM VALUE
    SAA    - SAPLINGS AVAILABLE (AREA/YEAR)
    FDH    - FLOW DIVERTED HABITATS (AREA/YEAR)
    SOM6   - SALE OLD GROWTH + MATURE + POLE-10 + POLE-8
               + POLE-6 (AREA/YEAR)
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MSA.K=ISAS.K*FSA                                              58, A
FSA=(TAH*SAF)/ROT                                             58.1, N
SAF=FIFZE(ST,NS,SAFI)                                         58.2, N
SAFI=(MAX(ASA,ROT))-(MIN(AP6,ROT))                            58.3, N
ASA=DSE                                                       58.4, N
     MSA     - MINIMUM SAPLING SALES (AREA/YEAR)
     ISAS    - INDICATED SAPLING SALES (DIMENSIONLESS)
     FSA     - FLOW SAPLING HABITATS (AREA/YEAR)
     TAH     - TOTAL AREA ALL HABITATS (AREA)
     SAF     - FRACTION REMOVED THROUGH SAPLING HABITAT
                 (PERCENT)
     ROT     - ROTATION SELECTED FOR RATE OF HARVEST
                 (YEARS)
     FIFZE   - FIRST IF THIRD IS ZERO
     ST      - STANDARD VALUE OF 1 (DIMENSIONLESS)
     NS      - NAUGHT STANDARD VALUE (ZERO)
     SAFI    - SAPLING FRACTION INDICATOR (YEARS)
     MAX     - FUNCTION SELECTS MAXIMUM VALUE
     ASA     - TRANSITION AGE SAPLINGS (YEARS)
     MIN     - FUNCTION SELECTS MINIMUM VALUE
     AP6     - TRANSITION AGE POLE-6 (YEARS)
     DSE     - DELAY FOR SEEDLING SUCCESSION (YEARS)

SAA.K=FIFGE(LSA.K,MSA.K,CSA.K,S)                              59, A
     SAA     - SAPLINGS AVAILABLE (AREA/YEAR)
     FIFGE   - FIRST IF THIRD GREATER OR EQUAL THE FOURTH
     LSA     - LIQUIDATE SAPLINGS (AREA/YEAR)
     MSA     - MINIMUM SAPLING SALES (AREA/YEAR)
     CSA     - COVERAGE OF SAPLINGS HABITAT
                 (DIMENSIONLESS)
     S       - VARIABLE STANDARD (DIMENSIONLESS)

ISAS.K=TABHL(TIMS,CSA.K,.5,1,.1)                              60, A
     ISAS    - INDICATED SAPLING SALES (DIMENSIONLESS)
     TIMS    - TABLE INDICATED TIMBER SALES
     CSA     - COVERAGE OF SAPLINGS HABITAT
                 (DIMENSIONLESS)

CSA.K=SAR.K/(FSA+E)                                           61, A
     CSA     - COVERAGE OF SAPLINGS HABITAT
                 (DIMENSIONLESS)
     SAR     - SAPLING RESERVES (AREA)
     FSA     - FLOW SAPLING HABITATS (AREA/YEAR)
     E       - EQUILIBRIUM CONSTANT (DIMENSION OF
                 VARIABLE)

LSA.K=MIN(SAR.K,FDH)                                          62, A
     LSA     - LIQUIDATE SAPLINGS (AREA/YEAR)
     MIN     - FUNCTION SELECTS MINIMUM VALUE
     SAR     - SAPLING RESERVES (AREA)
     FDH     - FLOW DIVERTED HABITATS (AREA/YEAR)
```

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SE.K=SE.J+DT*(ROG.JK+RMT.JK+RP1.JK+RP8.JK+RP6.JK+    63, L
  RSA.JK-SSH.JK)
SE=ISE                                                63.1, N
    SE      - SEEDLING HABITAT (AREA)
    ROG     - REMOVE OLD GROWTH (AREA/YEAR)
    RMT     - REMOVE MATURE HABITAT (AREA/YEAR)
    RP1     - REMOVE POLE-10 HABITAT (AREA/YEAR)
    RP8     - REMOVE POLE-8 HABITAT (AREA/YEAR)
    RP6     - REMOVE POLE-6 HABITAT (AREA/YEAR)
    RSA     - REMOVE SAPLINGS HABITAT (AREA/YEAR)
    SSH     - SUCCESSION TO SAPLING HABITAT (AREA/YEAR)
    ISE     - INVENTORY SEEDLINGS (AREA)

SSH.KL=SE.K/DSE                                       64, R
    SSH     - SUCCESSION TO SAPLING HABITAT (AREA/YEAR)
    SE      - SEEDLING HABITAT (AREA)
    DSE     - DELAY FOR SEEDLING SUCCESSION (YEARS)

SAR.K=SAR.J+DT*(SSH.JK-SAS.JK-SPH.JK)                 65, L
SAR=ISA                                               65.1, N
    SAR     - SAPLING RESERVES (AREA)
    SSH     - SUCCESSION TO SAPLING HABITAT (AREA/YEAR)
    SAS     - SAPLING SALES (AREA/YEAR)
    SPH     - SUCCESSION TO POLE HABITAT (AREA/YEAR)
    ISA     - INVENTORY SAPLINGS (AREA)

SPH.KL=SAR.K/DSA                                      66, R
    SPH     - SUCCESSION TO POLE HABITAT (AREA/YEAR)
    SAR     - SAPLING RESERVES (AREA)
    DSA     - DELAY FOR SAPLING SUCCESSION (YEARS)

P6R.K=P6R.J+DT*(SPH.JK-P6S.JK-SP8.JK)                 67, L
P6R=IP6                                               67.1, N
    P6R     - POLE-6 RESERVES (AREA)
    SPH     - SUCCESSION TO POLE HABITAT (AREA/YEAR)
    P6S     - POLE-6 SALES (AREA/YEAR)
    SP8     - SUCCESSION TO POLE-8 (AREA/YEAR)
    IP6     - INVENTORY POLE-6 (AREA)

SP8.KL=P6R.K/DP6                                      68, R
    SP8     - SUCCESSION TO POLE-8 (AREA/YEAR)
    P6R     - POLE-6 RESERVES (AREA)
    DP6     - DELAY FOR POLE-6 SUCCESSION (YEARS)

P8R.K=P8R.J+DT*(SP8.JK-P8S.JK-SP1.JK)                 69, L
P8R=IP8                                               69.1, N
    P8R     - POLE-8 RESERVES (AREA)
    SP8     - SUCCESSION TO POLE-8 (AREA/YEAR)
    P8S     - POLE-8 SALES (AREA/YEAR)
    SP1     - SUCCESSION TO POLE-10 (AREA/YEAR)
    IP8     - INVENTORY POLE-8 (AREA)

SP1.KL=P8R.K/DP8                                      70, R
    SP1     - SUCCESSION TO POLE-10 (AREA/YEAR)
    P8R     - POLE-8 RESERVES (AREA)
    DP8     - DELAY FOR POLE-8 SUCCESSION (YEARS)
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P1R.K=P1R.J+DT*(SP1.JK-P1S.JK-SMT.JK)                    71, L
P1R=IP1                                                  71.1, N
    P1R    - POLE-10 RESERVES (AREA)
    SP1    - SUCCESSION TO POLE-10 (AREA/YEAR)
    P1S    - POLE-10 SALES (AREA/YEAR)
    SMT    - SUCCESSION TO MATURE TIMBER (AREA/YEAR)
    IP1    - INVENTORY POLE-10 (AREA)

SMT.KL=P1R.K/DP1                                         72, R
    SMT    - SUCCESSION TO MATURE TIMBER (AREA/YEAR)
    P1R    - POLE-10 RESERVES (AREA)
    DP1    - DELAY FOR POLE-10 SUCCESSION (YEARS)

MTR.K=MTR.J+DT*(SMT.JK-MTS.JK-SOG.JK)                    73, L
MTR=IMT                                                  73.1, N
    MTR    - MATURE TIMBER RESERVES (AREA)
    SMT    - SUCCESSION TO MATURE TIMBER (AREA/YEAR)
    MTS    - MATURE TIMBER SALES (AREA/YEAR)
    SOG    - SUCCESSION TO OLD GROWTH (AREA/YEAR)
    IMT    - INVENTORY MATURE TIMBER (AREA)

SOG.KL=MTR.K/DMT                                         74, R
    SOG    - SUCCESSION TO OLD GROWTH (AREA/YEAR)
    MTR    - MATURE TIMBER RESERVES (AREA)
    DMT    - DELAY FOR MATURE HABITAT SUCCESSION (YEARS)

OGR.K=OGR.J+DT*(SOG.JK-OGS.JK)                           75, L
OGR=IOG                                                  75.1, N
    OGR    - OLD GROWTH RESERVES (AREA)
    SOG    - SUCCESSION TO OLD GROWTH (AREA/YEAR)
    OGS    - OLD GROWTH SALES (AREA/YEAR)
    IOG    - INVENTORY OLD GROWTH (AREA)
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SA.K=SAR.K+SASA.K                                          76, S
    SA      - SAPLING HABITAT (AREA)
    SAR     - SAPLING RESERVES (AREA)
    SASA    - SAPLING SALES ACCUMULATION (AREA)

P6.K=P6R.K+P6SA.K                                          77, S
    P6      - POLE 6-INCH HABITAT (AREA)
    P6R     - POLE-6 RESERVES (AREA)
    P6SA    - POLE-6 SALES ACCUMULATION (AREA)

P8.K=P8R.K+P8SA.K                                          78, S
    P8      - POLE 8-INCH HABITAT (AREA)
    P8R     - POLE-8 RESERVES (AREA)
    P8SA    - POLE-8 SALES ACCUMULATION (AREA)

P1.K=P1R.K+P1SA.K                                          79, S
    P1      - POLE 10-INCH HABITAT (AREA)
    P1R     - POLE-10 RESERVES (AREA)
    P1SA    - POLE-10 SALES ACCUMULATION (AREA)

MT.K=MTR.K+MHA.K                                           80, S
    MT      - MATURE TIMBER HABITAT (AREA)
    MTR     - MATURE TIMBER RESERVES (AREA)
    MHA     - MATURE HABITAT SALES ACCUMULATION (AREA)

OG.K=OGR.K+OSA.K                                           81, S
    OG      - OLD GROWTH HABITAT (AREA)
    OGR     - OLD GROWTH RESERVES (AREA)
    OSA     - OLD GROWTH SALES ACCUMULATION (AREA)

PSE.K=SE.K/TAH                                             82, S
    PSE     - PROPORTION OF AREA IN SEEDLING HABITAT
              (PERCENT)
    SE      - SEEDLING HABITAT (AREA)
    TAH     - TOTAL AREA ALL HABITATS (AREA)

PSA.K=SA.K/TAH                                             83, S
    PSA     - PROPORTION OF AREA IN SAPLING HABITAT
              (PERCENT)
    SA      - SAPLING HABITAT (AREA)
    TAH     - TOTAL AREA ALL HABITATS (AREA)

PP6.K=P6.K/TAH                                             84, S
    PP6     - PROPORTION OF AREA IN POLE-6 HABITAT
              (PERCENT)
    P6      - POLE 6-INCH HABITAT (AREA)
    TAH     - TOTAL AREA ALL HABITATS (AREA)

PP8.K=P8.K/TAH                                             85, S
    PP8     - PROPORTION OF AREA IN POLE-8 HABITAT
              (PERCENT)
    P8      - POLE 8-INCH HABITAT (AREA)
    TAH     - TOTAL AREA ALL HABITATS (AREA)
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PP1.K=P1.K/TAH                                              86, S
     PP1     - PROPORTION OF AREA IN POLE-10 HABITAT
                 (PERCENT)
     P1      - POLE 10-INCH HABITAT (AREA)
     TAH     - TOTAL AREA ALL HABITATS (AREA)

PMT.K=MT.K/TAH                                              87, S
     PMT     - PROPORTION OF AREA IN MATURE TIMBER HABITAT
                 (PERCENT)
     MT      - MATURE TIMBER HABITAT (AREA)
     TAH     - TOTAL AREA ALL HABITATS (AREA)

POG.K=OG.K/TAH                                              88, S
     POG     - PROPORTION OF AREA IN OLD GROWTH HABITAT
                 (PERCENT)
     OG      - OLD GROWTH HABITAT (AREA)
     TAH     - TOTAL AREA ALL HABITATS (AREA)

PSEA.K=(SE.K+SA.K)/TAH                                      89, S
     PSEA    - PROPORTION OF AREA IN SEEDLINGS AND
                 SAPLINGS (PERCENT)
     SE      - SEEDLING HABITAT (AREA)
     SA      - SAPLING HABITAT (AREA)
     TAH     - TOTAL AREA ALL HABITATS (AREA)

P08M.K=(P8.K+P1.K+MT.K)/TAH                                 90, S
     P08M    - PROPORTION OF AREA IN POLE-8,POLE-10 AND
                 MATURE HABITATS(PERCENT)
     P8      - POLE 8-INCH HABITAT (AREA)
     P1      - POLE 10-INCH HABITAT (AREA)
     MT      - MATURE TIMBER HABITAT (AREA)
     TAH     - TOTAL AREA ALL HABITATS (AREA)

P1M.K=(P1.K+MT.K)/TAH                                       91, S
     P1M     - PROPORTION OF AREA IN POLE-10 AND MATURE
                 HABITATS (PERCENT)
     P1      - POLE 10-INCH HABITAT (AREA)
     MT      - MATURE TIMBER HABITAT (AREA)
     TAH     - TOTAL AREA ALL HABITATS (AREA)

PMO.K=(MT.K+OG.K)/TAH                                       92, S
     PMO     - PROPORTION OF AREA IN MATURE AND OLD GROWTH
                 HABITATS (PERCENT)
     MT      - MATURE TIMBER HABITAT (AREA)
     OG      - OLD GROWTH HABITAT (AREA)
     TAH     - TOTAL AREA ALL HABITATS (AREA)
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SO.K=NORMRN(OPS.K,SDO)                                    93, S
SDO=MIN(ISD,(FDH/10))                                     93.1, N
    SO      - SIZE OF OPENING (AREA)
    NORMRN  - NORMAL DEVIATE RANDOM NUMBER FUNCTION
    OPS     - OPENING SIZE DISTRIBUTION (PROPORTIONAL
              AREA)
    SDO     - STANDARD DEVIATION OPENINGS (AREA)
    MIN     - FUNCTION SELECTS MINIMUM VALUE
    ISD     - OPENING VARIANCE DESIRED DIVIDED BY 2.4
              (AREA)
    FDH     - FLOW DIVERTED HABITATS (AREA/YEAR)

OPS.K=MIN(ISO,FDH)                                        94, S
    OPS     - OPENING SIZE DISTRIBUTION (PROPORTIONAL
              AREA)
    MIN     - FUNCTION SELECTS MINIMUM VALUE
    ISO     - SIZE OF OPENING SELECTED (AREA)
    FDH     - FLOW DIVERTED HABITATS (AREA/YEAR)

NOP.K=FDH/SO.K                                            95, S
    NOP     - NUMBER OF OPENINGS (NUMBER)
    FDH     - FLOW DIVERTED HABITATS (AREA/YEAR)
    SO      - SIZE OF OPENING (AREA)

OPM.K=NOP.K/(TAH/640)                                     96, S
    OPM     - NUMBER OF OPENINGS PER SQUARE MILE (NUMBER/
              SQUARE MILE)
    NOP     - NUMBER OF OPENINGS (NUMBER)
    TAH     - TOTAL AREA ALL HABITATS (AREA)
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PTI.K=TVI.K*SOF.K                                          97, S
    PTI    - POTENTIAL TIMBER INDEX (DIMENSIONLESS)
    TVI    - TIMBER VOLUME INDEX (DIMENSIONLESS)
    SOF    - SIZE OF OPENING FACTOR (DIMENSIONLESS)

TVI.K=(TVO.K+TVM.K+TV1.K+TV8.K+TV6.K+TVSA.K)/TIM           98, S
TIM=(TAH/TMR)*TYI                                          98.1, N
TYI=TABHL(TTYI,TMR,20,320,30)                              98.2, N
TTYI=.41/1/1.47/1.85/1.94/1.98/2.01/2.03/2.05/2.07/        98.3, T
  2.09
TMR=50                                                     98.4, C
    TVI    - TIMBER VOLUME INDEX (DIMENSIONLESS)
    TVO    - TIMBER VOLUME OLD GROWTH (VOLUME UNITS)
    TVM    - TIMBER VOLUME MATURE TIMBER (VOLUME UNITS)
    TV1    - TIMBER VOLUME POLE-10 (VOLUME UNITS)
    TV8    - TIMBER VOLUME POLE-8 (VOLUME UNITS)
    TV6    - TIMBER VOLUME POLE-6 (VOLUME UNITS)
    TVSA   - TIMBER VOLUME INDEX (VOLUME UNITS/ACRE)
    TIM    - TIMBER INDEX MAXIMUM (VOLUME UNITS)
    TAH    - TOTAL AREA ALL HABITATS (AREA)
    TMR    - TIMBER MAXIMUM ROTATION AGE (YEARS)
    TYI    - TIMBER YIELD INDEX (VOLUME UNITS/UNIT AREA/
               YEAR)
    TTYI   - TABLE TIMBER YIELD INDEX (VOLUME UNITS/UNIT
               AREA/YEAR)

TVO.K=ROG.JK*OGVF.K                                        99, S
    TVO    - TIMBER VOLUME OLD GROWTH (VOLUME UNITS)
    ROG    - REMOVE OLD GROWTH (AREA/YEAR)
    OGVF   - OLD GROWTH VOLUME FACTOR (VOLUME UNITS/
               AREA)

OGVF.K=TABHL(TTYI,HAOG.K,20,320,30)                        100, S
    OGVF   - OLD GROWTH VOLUME FACTOR (VOLUME UNITS/
               AREA)
    TTYI   - TABLE TIMBER YIELD INDEX (VOLUME UNITS/UNIT
               AREA/YEAR)
    HAOG   - HARVEST AGE OLD GROWTH (YEARS)

HAOG.K=(OG.K/FDH)+(AOG-1)                                  101, S
    HAOG   - HARVEST AGE OLD GROWTH (YEARS)
    OG     - OLD GROWTH HABITAT (AREA)
    FDH    - FLOW DIVERTED HABITATS (AREA/YEAR)
    AOG    - TRANSITION AGE OLD GROWTH (YEARS)

TVM.K=RMT.JK*MTVF.K                                        102, S
    TVM    - TIMBER VOLUME MATURE TIMBER (VOLUME UNITS)
    RMT    - REMOVE MATURE HABITAT (AREA/YEAR)
    MTVF   - MATURE TIMBER VOLUME FACTOR (VOLUME UNITS/
               AREA)

MTVF.K=TABHL(TTYI,HAMT.K,20,320,30)                        103, S
    MTVF   - MATURE TIMBER VOLUME FACTOR (VOLUME UNITS/
               AREA)
    TTYI   - TABLE TIMBER YIELD INDEX (VOLUME UNITS/UNIT
               AREA/YEAR)
    HAMT   - HARVEST AGE MATURE TIMBER (YEARS)
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HAMT.K=(MT.K/FDH)+(AMT-1)                                    104, S
    HAMT   - HARVEST AGE MATURE TIMBER (YEARS)
    MT     - MATURE TIMBER HABITAT (AREA)
    FDH    - FLOW DIVERTED HABITATS (AREA/YEAR)
    AMT    - TRANSITION AGE MATURE (YEARS)

TV1.K=RP1.JK*P1VF.K                                          105, S
    TV1    - TIMBER VOLUME POLE-10 (VOLUME UNITS)
    RP1    - REMOVE POLE-10 HABITAT (AREA/YEAR)
    P1VF   - POLE-10 VOLUME UNITS FACTOR (VOLUME UNITS/
               AREA)

P1VF.K=TABHL(TTYI,HAP1.K,20,320,30)                          106, S
    P1VF   - POLE-10 VOLUME UNITS FACTOR (VOLUME UNITS/
               AREA)
    TTYI   - TABLE TIMBER YIELD INDEX (VOLUME UNITS/UNIT
               AREA/YEAR)
    HAP1   - HARVEST AGE POLE-10 (YEARS)

HAP1.K=(P1.K/FDH)+(AP1-1)                                    107, S
    HAP1   - HARVEST AGE POLE-10 (YEARS)
    P1     - POLE 10-INCH HABITAT (AREA)
    FDH    - FLOW DIVERTED HABITATS (AREA/YEAR)
    AP1    - TRANSITION AGE POLE-10 (YEARS)

TV8.K=RP8.JK*P8VF.K                                          108, S
    TV8    - TIMBER VOLUME POLE-8 (VOLUME UNITS)
    RP8    - REMOVE POLE-8 HABITAT (AREA/YEAR)
    P8VF   - POLE-8 VOLUME UNITS FACTOR (VOLUME UNITS/
               AREA)

P8VF.K=TABHL(TTYI,HAP8.K,20,320,30)                          109, S
    P8VF   - POLE-8 VOLUME UNITS FACTOR (VOLUME UNITS/
               AREA)
    TTYI   - TABLE TIMBER YIELD INDEX (VOLUME UNITS/UNIT
               AREA/YEAR)
    HAP8   - HARVEST AGE POLE-8 (YEARS)

HAP8.K=(P8.K/FDH)+(AP8-1)                                    110, S
    HAP8   - HARVEST AGE POLE-8 (YEARS)
    P8     - POLE 8-INCH HABITAT (AREA)
    FDH    - FLOW DIVERTED HABITATS (AREA/YEAR)
    AP8    - TRANSITION AGE POLE-8 (YEARS)

TV6.K=RP6.JK*P6VF.K                                          111, S
    TV6    - TIMBER VOLUME POLE-6 (VOLUME UNITS)
    RP6    - REMOVE POLE-6 HABITAT (AREA/YEAR)
    P6VF   - POLE-6 VOLUME UNITS FACTOR (VOLUME UNITS/
               AREA)

P6VF.K=TABHL(TTYI,HAP6.K,20,320,30)                          112, S
    P6VF   - POLE-6 VOLUME UNITS FACTOR (VOLUME UNITS/
               AREA)
    TTYI   - TABLE TIMBER YIELD INDEX (VOLUME UNITS/UNIT
               AREA/YEAR)
    HAP6   - HARVEST AGE POLE-6 (YEARS)
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HAP6.K=(P6.K/FDH)+(AP6-1)                                    113, S
    HAP6   - HARVEST AGE POLE-6 (YEARS)
    P6     - POLE 6-INCH HABITAT (AREA)
    FDH    - FLOW DIVERTED HABITATS (AREA/YEAR)
    AP6    - TRANSITION AGE POLE-6 (YEARS)

TVSA.K=RSA.JK*SAVF.K                                         114, S
    TVSA   - TIMBER VOLUME INDEX (VOLUME UNITS/ACRE)
    RSA    - REMOVE SAPLINGS HABITAT (AREA/YEAR)
    SAVF   - SAPLING VOLUME FACTOR (VOLUME UNITS)

SAVF.K=TABHL(TTYI,HASA.K,20,320,30)                          115, S
    SAVF   - SAPLING VOLUME FACTOR (VOLUME UNITS)
    TTYI   - TABLE TIMBER YIELD INDEX (VOLUME UNITS/UNIT
             AREA/YEAR)
    HASA   - HARVEST AGE SAPLINGS (YEARS)

HASA.K=(SA.K/FDH)+(ASA-1)                                    116, S
    HASA   - HARVEST AGE SAPLINGS (YEARS)
    SA     - SAPLING HABITAT (AREA)
    FDH    - FLOW DIVERTED HABITATS (AREA/YEAR)
    ASA    - TRANSITION AGE SAPLINGS (YEARS)

SOF.K=TABHL(TOFM,SO.K,0,3,.5)                                117, S
TOFM=.5/.8/.9/.93/.95/.98/1                                  117.1, T
    SOF    - SIZE OF OPENING FACTOR (DIMENSIONLESS)
    TOFM   - TABLE OPENING FACTOR MULTIPLIER
             (DIMENSIONLESS)
    SO     - SIZE OF OPENING (AREA)

SEMT.K=TABHL(TSEMT,OPM.K,0,1,.2)                             118, S
TSEMT=0/.3/.6/.8/.9/1                                        118.1, T
    SEMT   - SEDIMENT INDEX (DIMENSIONLESS)
    TSEMT  - TABLE SEDIMENT INDEX
    OPM    - NUMBER OF OPENINGS PER SQUARE MILE (NUMBER/
             SQUARE MILE)

VIS.K=VSE.K*VBAL.K*VPOG.K                                    119, S
    VIS    - VISUAL APPEAL INDEX (DIMENSIONLESS)
    VSE    - VISUAL DUE TO SEEDLING HABITAT
             (DIMENSIONLESS)
    VBAL   - VISUAL APPEAL DUE TO BALANCED CONTRAST
             (DIMENSIONLESS)
    VPOG   - VISUAL DUE TO OLD GROWTH HABITATS
             (DIMENSIONLESS)

VSE.K=TABHL(TVSE,PSE.K,.01,.07,.01)                          120, S
TVSE=.2/.6/.9/1/.9/.6/.2                                     120.1, T
    VSE    - VISUAL DUE TO SEEDLING HABITAT
             (DIMENSIONLESS)
    TVSE   - TABLE VISUAL DUE TO SEEDLINGS
    PSE    - PROPORTION OF AREA IN SEEDLING HABITAT
             (PERCENT)
```

```
VBAL.K=TABHL(TVBA,BAL.K,0,2,.5)                                  121, S
TVBA=.4/.7/1/.7/.4                                               121.1, T
    VBAL   - VISUAL APPEAL DUE TO BALANCED CONTRAST
             (DIMENSIONLESS)
    TVBA   - TABLE VISUAL FOR BALANCE
    BAL    - BALANCE OF TALL AND SHORT HABITATS
             (DIMENSIONLESS)

BAL.K=(P8.K+P1.K+MT.K)/(SE.K+SA.K+P6.K)                          122, S
    BAL    - BALANCE OF TALL AND SHORT HABITATS
             (DIMENSIONLESS)
    P8     - POLE 8-INCH HABITAT (AREA)
    P1     - POLE 10-INCH HABITAT (AREA)
    MT     - MATURE TIMBER HABITAT (AREA)
    SE     - SEEDLING HABITAT (AREA)
    SA     - SAPLING HABITAT (AREA)
    P6     - POLE 6-INCH HABITAT (AREA)

VPOG.K=TABHL(TVPO,POG.K,0,.7,.1)                                 123, S
TVPO=.4/.7/.9/1/.9/.8/.6/.4                                      123.1, T
    VPOG   - VISUAL DUE TO OLD GROWTH HABITATS
             (DIMENSIONLESS)
    TVPO   - TABLE VISUAL OLD GROWTH
    POG    - PROPORTION OF AREA IN OLD GROWTH HABITAT
             (PERCENT)

UGL.K=UGS.K*UGN.K*UGO.K                                          124, S
    UGL    - UGLINESS INDEX (DIMENSIONLESS)
    UGS    - UGLY DUE TO SEEDLINGS (DIMENSIONLESS)
    UGN    - UGLY DUE TO NUMBER OF OPENINGS
             (DIMENSIONLESS)
    UGO    - UGLINESS DUE TO OPENING SIZE DISTRIBUTION
             (DIMENSIONLESS)

UGS.K=TABHL(TUGS,PSE.K,0,.06,.01)                                125, S
TUGS=0/.1/.2/.3/.5/.7/1                                          125.1, T
    UGS    - UGLY DUE TO SEEDLINGS (DIMENSIONLESS)
    TUGS   - TABLE UGLY FOR SEEDLINGS
    PSE    - PROPORTION OF AREA IN SEEDLING HABITAT
             (PERCENT)

UGN.K=TABHL(TUGN,OPM.K,0,.8,.2)                                  126, S
TUGN=1/.9/.7/.4/.01                                              126.1, T
    UGN    - UGLY DUE TO NUMBER OF OPENINGS
             (DIMENSIONLESS)
    TUGN   - TABLE UGLY FOR NUMBER OF OPENINGS
    OPM    - NUMBER OF OPENINGS PER SQUARE MILE (NUMBER/
             SQUARE MILE)

UGO.K=TABHL(TUGO,OPS.K,0,30,3)                                   127, S
TUGO=0/.50/.65/.7/.75/.8/.85/.9/.95/.97/1                        127.1, T
    UGO    - UGLINESS DUE TO OPENING SIZE DISTRIBUTION
             (DIMENSIONLESS)
    TUGO   - TABLE UGLINESS DUE TO OPENING SIZE
    OPS    - OPENING SIZE DISTRIBUTION (PROPORTIONAL
             AREA)
```

```
BEAR.K=BDT.K*BSMT.K*BHMT.K                                    128, S
    BEAR   - BEAR HABITAT INDEX (DIMENSIONLESS)
    BDT    - BEAR DEN HABITAT (DIMENSIONLESS)
    BSMT   - BEAR SOFT MAST TYPE (DIMENSIONLESS)
    BHMT   - BEAR HARD MAST TYPE (DIMENSIONLESS)

BDT.K=TABHL(TBDT,POG.K,0,.3,.1)                               129, S
TBDT=.2/.8/.9/1                                               129.1, T
    BDT    - BEAR DEN HABITAT (DIMENSIONLESS)
    TBDT   - TABLE BEAR DEN TYPE
    POG    - PROPORTION OF AREA IN OLD GROWTH HABITAT
               (PERCENT)

BSMT.K=TABHL(TBSM,PSEA.K,0,.2,.1)                             130, S
TBSM=0/.5/1                                                   130.1, T
    BSMT   - BEAR SOFT MAST TYPE (DIMENSIONLESS)
    TBSM   - TABLE BEAR SOFT MAST
    PSEA   - PROPORTION OF AREA IN SEEDLINGS AND
               SAPLINGS (PERCENT)

BHMT.K=TABHL(TBHM,PO8M.K,0,.4,.1)                             131, S
TBHM=0/.2/.4/.8/1                                             131.1, T
    BHMT   - BEAR HARD MAST TYPE (DIMENSIONLESS)
    TBHM   - TABLE BEAR HARD MAST
    PO8M   - PROPORTION OF AREA IN POLE-8,POLE-10 AND
               MATURE HABITATS (PERCENT)

DEER.K=HTD.K*OTD.K*DMA.K                                      132, S
    DEER   - DEER HABITAT INDEX (DIMENSIONLESS)
    HTD    - HABITAT TYPE DEER (DIMENSIONLESS)
    OTD    - OPENING TYPE DEER (DIMENSIONLESS)
    DMA    - DEER MAST AVAILABILITY (DIMENSIONLESS)

HTD.K=TABHL(THTD,PSE.K,0,.07,.01)                             133, S
THTD=0/.1/.2/.5/.7/.8/.9/1                                    133.1, T
    HTD    - HABITAT TYPE DEER (DIMENSIONLESS)
    THTD   - TABLE HABITAT TYPE DEER
    PSE    - PROPORTION OF AREA IN SEEDLING HABITAT
               (PERCENT)

OTD.K=TABHL(TOTD,OPS.K,0,60,6)                                134, S
TOTD=1/1/.97/.93/.9/.85/.8/.7/.6/.5/.45                       134.1, T
    OTD    - OPENING TYPE DEER (DIMENSIONLESS)
    TOTD   - TABLE OPENING TYPE DEER
    OPS    - OPENING SIZE DISTRIBUTION (PROPORTIONAL
               AREA)

DMA.K=TABHL(TDMA,P1M.K,0,.2,.05)                              135, S
TDMA=.1/.2/.5/.8/1                                            135.1, T
    DMA    - DEER MAST AVAILABILITY (DIMENSIONLESS)
    TDMA   - TABLE DEER MAST AVAILABILITY
    P1M    - PROPORTION OF AREA IN POLE-10 AND MATURE
               HABITATS (PERCENT)
```

```
SQU.K=THS.K*SDT.K                                          136, S
    SQU    - SQUIRREL HABITAT INDEX (DIMENSIONLESS)
    THS    - TYPE HABITAT FOR SQUIRRELS (DIMENSIONLESS)
    SDT    - SQUIRREL DEN TREE INDEX (DIMENSIONLESS)

THS.K=TABHL(TTHS,PO8M.K,0,.4,.1)                           137, S
TTHS=0/.2/.4/.8/1                                          137.1, T
    THS    - TYPE HABITAT FOR SQUIRRELS (DIMENSIONLESS)
    TTHS   - TABLE TYPE HABITAT SQUIRRELS
    PO8M   - PROPORTION OF AREA IN POLE-8,POLE-10 AND
               MATURE HABITATS(PERCENT)

SDT.K=TABHL(TSDT,POG.K,0,.3,.1)                            138, S
TSDT=.1/.7/.8/1                                            138.1, T
    SDT    - SQUIRREL DEN TREE INDEX (DIMENSIONLESS)
    TSDT   - TABLE SQUIRREL DEN TREE
    POG    - PROPORTION OF AREA IN OLD GROWTH HABITAT
               (PERCENT)

TUR.K=TURT.K*TURO.K                                        139, S
    TUR    - TURKEY HABITAT INDEX (DIMENSIONLESS)
    TURT   - TURKEY TYPE HABITAT (DIMENSIONLESS)
    TURO   - TURKEY OPENING INDEX (DIMENSIONLESS)

TURT.K=TABHL(TTRT,PO8M.K,0,.5,.1)                          140, S
TTRT=0/.1/.2/.5/.8/1                                       140.1, T
    TURT   - TURKEY TYPE HABITAT (DIMENSIONLESS)
    TTRT   - TABLE TURKEY TYPE
    PO8M   - PROPORTION OF AREA IN POLE-8,POLE-10 AND
               MATURE HABITATS(PERCENT)

TURO.K=TABHL(TTRO,OPS.K,0,28,2)                            141, S
TTRO=0/.2/.5/.7/.9/1/1/1/1/.9/.8/.7/.6/.5/.4               141.1, T
    TURO   - TURKEY OPENING INDEX (DIMENSIONLESS)
    TTRO   - TABLE TURKEY OPENINGS
    OPS    - OPENING SIZE DISTRIBUTION (PROPORTIONAL
               AREA)

GRS.K=GRH.K*GRO.K                                          142, S
    GRS    - GROUSE HABITAT INDEX (DIMENSIONLESS)
    GRH    - GROUSE HABITAT TYPE (DIMENSIONLESS)
    GRO    - GROUSE OPENING TYPE (DIMENSIONLESS)

GRH.K=TABHL(TGRH,PP6.K,0,.2,.05)                           143, S
TGRH=0/.2/.7/.9/1                                          143.1, T
    GRH    - GROUSE HABITAT TYPE (DIMENSIONLESS)
    TGRH   - TABLE GROUSE HABITAT
    PP6    - PROPORTION OF AREA IN POLE-6 HABITAT
               (PERCENT)

GRO.K=TABHL(TGRO,OPS.K,0,60,6)                             144, S
TGRO=.8/.9/.95/1/.95/.9/.85/.8/.7/.6/.5                    144.1, T
    GRO    - GROUSE OPENING TYPE (DIMENSIONLESS)
    TGRO   - TABLE GROUSE OPENINGS
    OPS    - OPENING SIZE DISTRIBUTION (PROPORTIONAL
               AREA)
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```
OVN.K=TABHL(TOVN,PP6.K,0,.3,.05)                                    145, S
TOVN=.1/.2/.4/.7/.8/.9/1                                            145.1, T
    OVN    - OVENBIRD HABITAT INDEX (DIMENSIONLESS)
    TOVN   - TABLE OVENBIRD
    PP6    - PROPORTION OF AREA IN POLE-6 HABITAT
             (PERCENT)

BLU.K=BBH.K*BBO.K                                                   146, S
    BLU    - BLUEBIRD HABITAT INDEX (DIMENSIONLESS)
    BBH    - BLUEBIRD HABITAT TYPE (DIMENSIONLESS)
    BBO    - BLUEBIRD OPENING TYPE (DIMENSIONLESS)

BBH.K=TABHL(TBBH,PSE.K,0,.06,.01)                                   147, S
TBBH=0/.1/.2/.4/.7/.9/1                                             147.1, T
    BBH    - BLUEBIRD HABITAT TYPE (DIMENSIONLESS)
    TBBH   - TABLE BLUEBIRD HABITAT
    PSE    - PROPORTION OF AREA IN SEEDLING HABITAT
             (PERCENT)

BBO.K=TABHL(TBBO,OPS.K,0,60,6)                                      148, S
TBBO=0/.6/1/1/1/1/.95/.9/.85/.8/.7                                  148.1, T
    BBO    - BLUEBIRD OPENING TYPE (DIMENSIONLESS)
    TBBO   - TABLE BLUEBIRD OPENING
    OPS    - OPENING SIZE DISTRIBUTION (PROPORTIONAL
             AREA)

PIL.K=TABHL(TPIL,POG.K,0,.6,.1)                                     149, S
TPIL=.1/.4/.6/.8/.9/.95/1                                           149.1, T
    PIL    - PILEATED WOODPECKER HABITAT INDEX
             (DIMENSIONLESS)
    TPIL   - TABLE PILEATED WOODPECKER
    POG    - PROPORTION OF AREA IN OLD GROWTH HABITAT
             (PERCENT)

FLIC.K=FLF.K*FLN.K*FLO.K                                            150, S
    FLIC   - FLICKER WOODPECKER HABITAT INDEX
             (DIMENSIONLESS)
    FLF    - FLICKER FOOD HABITAT (DIMENSIONLESS)
    FLN    - FLICKER NESTING HABITAT (DIMENSIONLESS)
    FLO    - FLICKER OPENING HABITAT (DIMENSIONLESS)

FLF.K=TABHL(TFLF,PSE.K,0,.06,.01)                                   151, S
TFLF=.05/.15/.3/.5/.7/.9/1                                          151.1, T
    FLF    - FLICKER FOOD HABITAT (DIMENSIONLESS)
    TFLF   - TABLE FLICKER FOOD
    PSE    - PROPORTION OF AREA IN SEEDLING HABITAT
             (PERCENT)

FLN.K=TABHL(TFLN,PMO.K,0,.2,.05)                                    152, S
TFLN=.5/.8/.9/.95/1                                                 152.1, T
    FLN    - FLICKER NESTING HABITAT (DIMENSIONLESS)
    TFLN   - TABLE FLICKER NESTING
    PMO    - PROPORTION OF AREA IN MATURE AND OLD GROWTH
             HABITATS (PERCENT)
```

```
FLO.K=TABHL(TFLO,OPS.K,0,10,2)                                  153, S
TFLO=.05/.1/.5/.9/.95/1                                         153.1, T
    FLO    - FLICKER OPENING HABITAT (DIMENSIONLESS)
    TFLO   - TABLE FLICKER OPENING
    OPS    - OPENING SIZE DISTRIBUTION (PROPORTIONAL
             AREA)

DON.K=TABHL(TDON,P1M.K,0,.4,.05)                                154, S
TDON=.1/.15/.3/.4/.6/.8/.9/.95/1                                154.1, T
    DON    - DOWNY WOODPECKER HABITAT INDEX
             (DIMENSIONLESS)
    TDON   - TABLE DOWNY WOODPECKER
    P1M    - PROPORTION OF AREA IN POLE-10 AND MATURE
             HABITATS (PERCENT)

TWE.K=TWH.K*TWO.K                                               155, S
    TWE    - TOWHEE HABITAT INDEX (DIMENSIONLESS)
    TWH    - TOWHEE HABITAT TYPE (DIMENSIONLESS)
    TWO    - TOWHEE OPENING TYPE (DIMENSIONLESS)

TWH.K=TABHL(TTWE,PSA.K,0,.45,.05)                               156, S
TTWE=0/.1/.2/.4/.6/.8/.85/.9/.95/1                              156.1, T
    TWH    - TOWHEE HABITAT TYPE (DIMENSIONLESS)
    TTWE   - TABLE TOWHEE HABITAT
    PSA    - PROPORTION OF AREA IN SAPLING HABITAT
             (PERCENT)

TWO.K=TABHL(TTWO,OPS.K,0,5,1)                                   157, S
TTWO=.1/.5/.7/.8/.9/1                                           157.1, T
    TWO    - TOWHEE OPENING TYPE (DIMENSIONLESS)
    TTWO   - TABLE TOWHEE OPENING
    OPS    - OPENING SIZE DISTRIBUTION (PROPORTIONAL
             AREA)

PWE.K=TABHL(TPWE,PMO.K,0,.7,.1)                                 158, S
TPWE=.1/.2/.4/.7/.8/.9/.95/1                                    158.1, T
    PWE    - PEEWEE HABITAT INDEX (DIMENSIONLESS)
    TPWE   - TABLE PEEWEE HABITAT
    PMO    - PROPORTION OF AREA IN MATURE AND OLD GROWTH
             HABITATS (PERCENT)

HAR.K=TABHL(THAR,PMO.K,0,.5,.05)                                159, S
THAR=.05/.1/.15/.2/.35/.5/.65/.8/.9/.95/1                       159.1, T
    HAR    - HAIRY WOODPECKER HABITAT INDEX
             (DIMENSIONLESS)
    THAR   - TABLE HAIRY WOODPECKER
    PMO    - PROPORTION OF AREA IN MATURE AND OLD GROWTH
             HABITATS (PERCENT)
```

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VT.K=VOG.K+VMT.K+VP1.K+VP8.K+VP6.K+VSA.K                    160, S
    VT      - VOLUME HARVESTED TOTAL TIMBER (CUBIC
              VOLUME)
    VOG     - VOLUME HARVESTED OLD GROWTH  (CUBIC VOLUME)
    VMT     - VOLUME HARVESTED MATURE TIMBER   (CUBIC
              VOLUME)
    VP1     - VOLUME HARVESTED POLE-10  (CUBIC VOLUME)
    VP8     - VOLUME HARVESTED POLE-8   (CUBIC VOLUME)
    VP6     - VOLUME HARVESTED POLE-6   (CUBIC VOLUME)
    VSA     - VOLUME HARVESTED SAPLINGS (CUBIC VOLUME)

VOG.K=Y50*TVO.K*SOF.K                                       161, S
    VOG     - VOLUME HARVESTED OLD GROWTH  (CUBIC VOLUME)
    Y50     - YIELD TABLE VOLUME, AGE 50 (CUBIC VOLUME)
    TVO     - TIMBER VOLUME OLD GROWTH (VOLUME UNITS)
    SOF     - SIZE OF OPENING FACTOR (DIMENSIONLESS)

VMT.K=Y50*TVM.K*SOF.K                                       162, S
    VMT     - VOLUME HARVESTED MATURE TIMBER   (CUBIC
              VOLUME)
    Y50     - YIELD TABLE VOLUME, AGE 50 (CUBIC VOLUME)
    TVM     - TIMBER VOLUME MATURE TIMBER (VOLUME UNITS)
    SOF     - SIZE OF OPENING FACTOR (DIMENSIONLESS)

VP1.K=Y50*TV1.K*SOF.K                                       163, S
    VP1     - VOLUME HARVESTED POLE-10  (CUBIC VOLUME)
    Y50     - YIELD TABLE VOLUME, AGE 50 (CUBIC VOLUME)
    TV1     - TIMBER VOLUME POLE-10 (VOLUME UNITS)
    SOF     - SIZE OF OPENING FACTOR (DIMENSIONLESS)

VP8.K=Y50*TV8.K*SOF.K                                       164, S
    VP8     - VOLUME HARVESTED POLE-8   (CUBIC VOLUME)
    Y50     - YIELD TABLE VOLUME, AGE 50 (CUBIC VOLUME)
    TV8     - TIMBER VOLUME POLE-8 (VOLUME UNITS)
    SOF     - SIZE OF OPENING FACTOR (DIMENSIONLESS)

VP6.K=Y50*TV6.K*SOF.K                                       165, S
    VP6     - VOLUME HARVESTED POLE-6   (CUBIC VOLUME)
    Y50     - YIELD TABLE VOLUME, AGE 50 (CUBIC VOLUME)
    TV6     - TIMBER VOLUME POLE-6 (VOLUME UNITS)
    SOF     - SIZE OF OPENING FACTOR (DIMENSIONLESS)

VSA.K=Y50*TVSA.K*SOF.K                                      166, S
Y50=2520                                                    166.1, C
    VSA     - VOLUME HARVESTED SAPLINGS (CUBIC VOLUME)
    Y50     - YIELD TABLE VOLUME, AGE 50 (CUBIC VOLUME)
    TVSA    - TIMBER VOLUME INDEX (VOLUME UNITS/ACRE)
    SOF     - SIZE OF OPENING FACTOR (DIMENSIONLESS)
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SPEC  DT=.25/LENGTH=170                                          166.3

PRTPER.K=1+STEP(39,11)                                           167, A

PRINT    1)OGS,VOG/2)MTS,VMT/3)P1S,VP1/4)P8S,VP8/5)  167.1
  P6S,VP6/6)SAS,VSA/
    OGS     - OLD GROWTH SALES (AREA/YEAR)
    VOG     - VOLUME HARVESTED OLD GROWTH  (CUBIC VOLUME)
    MTS     - MATURE TIMBER SALES (AREA/YEAR)
    VMT     - VOLUME HARVESTED MATURE TIMBER   (CUBIC
              VOLUME)
    P1S     - POLE-10 SALES (AREA/YEAR)
    VP1     - VOLUME HARVESTED POLE-10  (CUBIC VOLUME)
    P8S     - POLE-8 SALES (AREA/YEAR)
    VP8     - VOLUME HARVESTED POLE-8   (CUBIC VOLUME)
    P6S     - POLE-6 SALES (AREA/YEAR)
    VP6     - VOLUME HARVESTED POLE-6   (CUBIC VOLUME)
    SAS     - SAPLING SALES (AREA/YEAR)
    VSA     - VOLUME HARVESTED SAPLINGS (CUBIC VOLUME)

PRINT    7)PTI,VT/8)OG,MT/9)P1,P8/10)P6,SA/11)SE,    167.2
  SEMT/12)DEER,SQU/
    PTI     - POTENTIAL TIMBER INDEX (DIMENSIONLESS)
    VT      - VOLUME HARVESTED TOTAL TIMBER (CUBIC
              VOLUME)
    OG      - OLD GROWTH HABITAT (AREA)
    MT      - MATURE TIMBER HABITAT (AREA)
    P1      - POLE 10-INCH HABITAT (AREA)
    P8      - POLE 8-INCH HABITAT (AREA)
    P6      - POLE 6-INCH HABITAT (AREA)
    SA      - SAPLING HABITAT (AREA)
    SE      - SEEDLING HABITAT (AREA)
    SEMT    - SEDIMENT INDEX (DIMENSIONLESS)
    DEER    - DEER HABITAT INDEX (DIMENSIONLESS)
    SQU     - SQUIRREL HABITAT INDEX (DIMENSIONLESS)

PRINT    13)TUR,GRS/14)VIS,UGL                                   167.3
    TUR     - TURKEY HABITAT INDEX (DIMENSIONLESS)
    GRS     - GROUSE HABITAT INDEX (DIMENSIONLESS)
    VIS     - VISUAL APPEAL INDEX (DIMENSIONLESS)
    UGL     - UGLINESS INDEX (DIMENSIONLESS)

PLTPER.K=1+STEP(3,11)                                            168, A

PLOT  PSE=S(0,.4)/PSA=A,PP6=6,PP8=8,PP1=1,PMT=M,     168.1
  POG=O,(0,.8)
    PSE     - PROPORTION OF AREA IN SEEDLING HABITAT
              (PERCENT)
    PSA     - PROPORTION OF AREA IN SAPLING HABITAT
              (PERCENT)
    PP6     - PROPORTION OF AREA IN POLE-6 HABITAT
              (PERCENT)
    POG     - PROPORTION OF AREA IN OLD GROWTH HABITAT
              (PERCENT)
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PLOT  PTI=T,SEMT=I,BEAR=B,GRS=G,TUR=K,BLU=L,DEER=D,                168.2
  SQU=Q(0,1)
    PTI     - POTENTIAL TIMBER INDEX (DIMENSIONLESS)
    SEMT    - SEDIMENT INDEX (DIMENSIONLESS)
    BEAR    - BEAR HABITAT INDEX (DIMENSIONLESS)
    GRS     - GROUSE HABITAT INDEX (DIMENSIONLESS)
    TUR     - TURKEY HABITAT INDEX (DIMENSIONLESS)
    BLU     - BLUEBIRD HABITAT INDEX (DIMENSIONLESS)
    DEER    - DEER HABITAT INDEX (DIMENSIONLESS)
    SQU     - SQUIRREL HABITAT INDEX (DIMENSIONLESS)

PLOT  VIS=V,UGI=U,OVN=O,PIL=P,FLIC=F,DON=N,TWE=W,                  168.3
  PWE=E,HAR=H(0,1)
    VIS     - VISUAL APPEAL INDEX (DIMENSIONLESS)
    UGL     - UGLINESS INDEX (DIMENSIONLESS)
    OVN     - OVENBIRD HABITAT INDEX (DIMENSIONLESS)
    PIL     - PILEATED WOODPECKER HABITAT INDEX
              (DIMENSIONLESS)
    FLIC    - FLICKER WOODPECKER HABITAT INDEX
              (DIMENSIONLESS)
    DON     - DOWNY WOODPECKER HABITAT INDEX
              (DIMENSIONLESS)
    TWE     - TOWHEE HABITAT INDEX (DIMENSIONLESS)
    PWE     - PEEWEE HABITAT INDEX (DIMENSIONLESS)
    HAR     - HAIRY WOODPECKER HABITAT INDEX
              (DIMENSIONLESS)

DSE=5/DSA=30/DP6=15/DP8=15/DP1=20/DMT=35/DOG=180                   168.4, C
ISE=200/ISA=1254/IP6=1843/IP8=740/IP1=1809/IMT=366/                168.5, C
  IOG=185
ROT=20                                                             168.6, C
ISO=50/ISD=5                                                       168.7, C
    DSE     - DELAY FOR SEEDLING SUCCESSION (YEARS)
    DSA     - DELAY FOR SAPLING SUCCESSION (YEARS)
    DP6     - DELAY FOR POLE-6 SUCCESSION (YEARS)
    DP8     - DELAY FOR POLE-8 SUCCESSION (YEARS)
    DP1     - DELAY FOR POLE-10 SUCCESSION (YEARS)
    DMT     - DELAY FOR MATURE HABITAT SUCCESSION (YEARS)
    DOG     - DELAY FOR OLD GROWTH SUCCESSION (YEARS)
    ISE     - INVENTORY SEEDLINGS (AREA)
    ISA     - INVENTORY SAPLINGS (AREA)
    IP6     - INVENTORY POLE-6 (AREA)
    IP8     - INVENTORY POLE-8 (AREA)
    IP1     - INVENTORY POLE-10 (AREA)
    IMT     - INVENTORY MATURE TIMBER (AREA)
    IOG     - INVENTORY OLD GROWTH (AREA)
    ROT     - ROTATION SELECTED FOR RATE OF HARVEST
              (YEARS)
    ISO     - SIZE OF OPENING SELECTED (AREA)
    ISD     - OPENING VARIANCE DESIRED DIVIDED BY 2.4
              (AREA)
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APPENDIX B

ALPHABETICAL LIST OF VARIABLES, DEFINITIONS, AND UNITS OF MEASURE

NAME	NO	T	DEFINITION
AMT	15.4	N	TRANSITION AGE MATURE (YEARS)
AOG	5.7	N	TRANSITION AGE OLD GROWTH (YEARS)
AP1	26.4	N	TRANSITION AGE POLE-10 (YEARS)
AP6	48.4	N	TRANSITION AGE POLE-6 (YEARS)
AP8	37.4	N	TRANSITION AGE POLE-8 (YEARS)
ASA	58.4	N	TRANSITION AGE SAPLINGS (YEARS)
BAL	122	S	BALANCE OF TALL AND SHORT HABITATS (DIMENSIONLESS)
BBH	147	S	BLUEBIRD HABITAT TYPE (DIMENSIONLESS)
BBO	148	S	BLUEBIRD OPENING TYPE (DIMENSIONLESS)
BDT	129	S	BEAR DEN HABITAT (DIMENSIONLESS)
BEAR	128	S	BEAR HABITAT INDEX (DIMENSIONLESS)
BHMT	131	S	BEAR HARD MAST TYPE (DIMENSIONLESS)
BLU	146	S	BLUEBIRD HABITAT INDEX (DIMENSIONLESS)
BSMT	130	S	BEAR SOFT MAST TYPE (DIMENSIONLESS)
CMT	17	A	COVERAGE OF MATURE HABITAT (DIMENSIONLESS)
COG	7	A	COVERAGE OF OLD GROWTH HABITAT (DIMENSIONLESS)
CP1	28	A	COVERAGE OF POLE-10 HABITAT (DIMENSIONLESS)
CP6	50	A	COVERAGE OF POLE-6 HABITAT (DIMENSIONLESS)
CP8	39	A	COVERAGE OF POLE-8 HABITAT (DIMENSIONLESS)
CSA	61	A	COVERAGE OF SAPLINGS HABITAT (DIMENSIONLESS)
DEER	132	S	DEER HABITAT INDEX (DIMENSIONLESS)
DMA	135	S	DEER MAST AVAILABILITY (DIMENSIONLESS)
DMT			DELAY FOR MATURE HABITAT SUCCESSION (YEARS)
DOG			DELAY FOR OLD GROWTH SUCCESSION (YEARS)
DON	154	S	DOWNY WOODPECKER HABITAT INDEX (DIMENSIONLESS)
DP1			DELAY FOR POLE-10 SUCCESSION (YEARS)
DP6			DELAY FOR POLE-6 SUCCESSION (YEARS)
DP8			DELAY FOR POLE-8 SUCCESSION (YEARS)
DRT	1.1	C	DELAY FOR REMOVAL OF TIMBER (YEARS)
DSA			DELAY FOR SAPLING SUCCESSION (YEARS)
DSE	168.4	C	DELAY FOR SEEDLING SUCCESSION (YEARS)
E	7.1	C	EQUILIBRIUM CONSTANT (DIMENSION OF VARIABLE)
FDH	8.1	N	FLOW DIVERTED HABITATS (AREA/YEAR)
FIFGE			FIRST IF THIRD GREATER OR EQUAL THE FOURTH
FIFZE			FIRST IF THIRD IS ZERO
FLF	151	S	FLICKER FOOD HABITAT (DIMENSIONLESS)
FLIC	150	S	FLICKER WOODPECKER HABITAT INDEX (DIMENSIONLESS)
FLN	152	S	FLICKER NESTING HABITAT (DIMENSIONLESS)
FLO	153	S	FLICKER OPENING HABITAT (DIMENSIONLESS)
FMT	15.1	N	FLOW MATURE TIMBER HABITATS (AREA/YEAR)
FOG	5.1	N	FLOW OLD GROWTH HABITATS (AREA/YEAR)
FP1	26.1	N	FLOW POLE-10 HABITATS (AREA/YEAR)
FP6	48.1	N	FLOW POLE-6 HABITATS (AREA/YEAR)
FP8	37.1	N	FLOW POLE-8 HABITATS (AREA/YEAR)

FSA	58.1	N	FLOW SAPLING HABITATS (AREA/YEAR)
GRH	143	S	GROUSE HABITAT TYPE (DIMENSIONLESS)
GRO	144	S	GROUSE OPENING TYPE (DIMENSIONLESS)
GRS	142	S	GROUSE HABITAT INDEX (DIMENSIONLESS)
HAMT	104	S	HARVEST AGE MATURE TIMBER (YEARS)
HAOG	101	S	HARVEST AGE OLD GROWTH (YEARS)
HAP1	107	S	HARVEST AGE POLE-10 (YEARS)
HAP6	113	S	HARVEST AGE POLE-6 (YEARS)
HAP8	110	S	HARVEST AGE POLE-8 (YEARS)
HAR	159	S	HAIRY WOODPECKER HABITAT INDEX (DIMENSIONLESS)
HASA	116	S	HARVEST AGE SAPLINGS (YEARS)
HTD	133	S	HABITAT TYPE DEER (DIMENSIONLESS)
IMT			INVENTORY MATURE TIMBER (AREA)
IMTS	16	A	INDICATED MATURE TIMBER SALES (DIMENSIONLESS)
IOG			INVENTORY OLD GROWTH (AREA)
IOGS	6	A	INDICATED OLD GROWTH SALES (DIMENSIONLESS)
IP1			INVENTORY POLE-10 (AREA)
IP1S	27	A	INDICATED POLE-10 SALES (DIMENSIONLESS)
IP6			INVENTORY POLE-6 (AREA)
IP6S	49	A	INDICATED POLE-6 SALES (DIMENSIONLESS)
IP8			INVENTORY POLE-8 (AREA)
IP8S	38	A	INDICATED POLE-8 SALES (DIMENSIONLESS)
ISA			INVENTORY SAPLINGS (AREA)
ISAS	60	A	INDICATED SAPLING SALES (DIMENSIONLESS)
ISD			OPENING VARIANCE DESIRED DIVIDED BY 2.4 (AREA)
ISE	168.5	C	INVENTORY SEEDLINGS (AREA)
ISO	168.7	C	SIZE OF OPENING SELECTED (AREA)
LENGTH			
LMT	18	A	LIQUIDATE MATURE HABITAT (AREA/YEAR)
LOG	8	A	LIQUIDATE OLD GROWTH (AREA/YEAR)
LP1	29	A	LIQUIDATE POLE-10 (AREA/YEAR)
LP6	51	A	LIQUIDATE POLE-6 (AREA/YEAR)
LP8	40	A	LIQUIDATE POLE-8 (AREA/YEAR)
LSA	62	A	LIQUIDATE SAPLINGS (AREA/YEAR)
MAX			FUNCTION SELECTS MAXIMUM VALUE
MHA	10	L	MATURE HABITAT SALES ACCUMULATION (AREA)
	10.1	N	
MIN			FUNCTION SELECTS MINIMUM VALUE
MMT	15	A	MINIMUM MATURE TIMBER SALES (AREA/YEAR)
MOG	5	A	MINIMUM OLD GROWTH SALES (AREA/YEAR)
MP1	26	A	MINIMUM POLE-10 SALES (AREA/YEAR)
MP6	48	A	MINIMUM POLE-6 SALES (AREA/YEAR)
MP8	37	A	MINIMUM POLE-8 SALES (AREA/YEAR)
MSA	58	A	MINIMUM SAPLING SALES (AREA/YEAR)
MT	80	S	MATURE TIMBER HABITAT (AREA)
MTA	14	A	MATURE TIMBER AVAILABLE (AREA/YEAR)
MTF	15.2	N	FRACTION REMOVED THROUGH MATURE HABITAT (PERCENT)
MTFI	15.3	N	MATURE TIMBER FRACTION INDICATOR (YEARS)
MTN	13	A	MATURE HABITAT NEEDED (AREA/YEAR)

MTR	73	L	MATURE TIMBER RESERVES (AREA)
	73.1	N	
MTS	11	R	MATURE TIMBER SALES (AREA/YEAR)
MTVF	103	S	MATURE TIMBER VOLUME FACTOR (VOLUME UNITS/ AREA)
NOP	95	S	NUMBER OF OPENINGS (NUMBER)
NORMRN			NORMAL DEVIATE RANDOM NUMBER FUNCTION
NS	5.6	C	NAUGHT STANDARD VALUE (ZERO)
OG	81	S	OLD GROWTH HABITAT (AREA)
OGF	5.3	N	FRACTION REMOVED THROUGH OLD GROWTH HABITAT (PERCENT)
OGFI	5.4	N	OLD GROWTH FRACTION INDICATOR (YEARS)
OGR	75	L	OLD GROWTH RESERVES (AREA)
	75.1	N	
OGS	3	R	OLD GROWTH SALES (AREA/YEAR)
OGVF	100	S	OLD GROWTH VOLUME FACTOR (VOLUME UNITS/ AREA)
OPM	96	S	NUMBER OF OPENINGS PER SQUARE MILE (NUMBER/ SQUARE MILE)
OPS	94	S	OPENING SIZE DISTRIBUTION (PROPORTIONAL AREA)
OSA	2	L	OLD GROWTH SALES ACCUMULATION (AREA)
	2.1	N	
OTD	134	S	OPENING TYPE DEER (DIMENSIONLESS)
OVN	145	S	OVENBIRD HABITAT INDEX (DIMENSIONLESS)
PIL	149	S	PILEATED WOODPECKER HABITAT INDEX (DIMENSIONLESS)
PLTPER	168	A	
PMO	92	S	PROPORTION OF AREA IN MATURE AND OLD GROWTH HABITATS (PERCENT)
PMT	87	S	PROPORTION OF AREA IN MATURE TIMBER HABITAT (PERCENT)
POG	88	S	PROPORTION OF AREA IN OLD GROWTH HABITAT (PERCENT)
POSM	90	S	PROPORTION OF AREA IN POLE-8,POLE-10 AND MATURE HABITATS(PERCENT)
PP1	86	S	PROPORTION OF AREA IN POLE-10 HABITAT (PERCENT)
PP6	84	S	PROPORTION OF AREA IN POLE-6 HABITAT (PERCENT)
PP8	85	S	PROPORTION OF AREA IN POLE-8 HABITAT (PERCENT)
PRTPER	167	A	
PSA	83	S	PROPORTION OF AREA IN SAPLING HABITAT (PERCENT)
PSE	82	S	PROPORTION OF AREA IN SEEDLING HABITAT (PERCENT)
PSEA	89	S	PROPORTION OF AREA IN SEEDLINGS AND SAPLINGS (PERCENT)
PTI	97	S	POTENTIAL TIMBER INDEX (DIMENSIONLESS)
PWE	158	S	PEEWEE HABITAT INDEX (DIMENSIONLESS)
P1	79	S	POLE 10-INCH HABITAT (AREA)
P1A	25	A	POLE-10 AVAILABLE (AREA/YEAR)
P1F	26.2	N	FRACTION REMOVED THROUGH POLE-10 HABITAT (PERCENT)
P1FI	26.3	N	POLE-10 FRACTION INDICATOR (YEARS)

P1M	91	S	PROPORTION OF AREA IN POLE-10 AND MATURE HABITATS (PERCENT)
P1N	24	A	POLE-10 HABITAT NEEDED (AREA/YEAR)
P1R	71	L	POLE-10 RESERVES (AREA)
	71.1	N	
P1S	21	R	POLE-10 SALES (AREA/YEAR)
P1SA	20	L	POLE-10 SALES ACCUMULATION (AREA)
	20.1	N	
P1VF	106	S	POLE-10 VOLUME UNITS FACTOR (VOLUME UNITS/ AREA)
P6	77	S	POLE 6-INCH HABITAT (AREA)
P6A	47	A	POLE-6 AVAILABLE (AREA/YEAR)
P6F	48.2	N	FRACTION REMOVED THROUGH POLE-6 HABITAT (PERCENT)
P6FI	48.3	N	POLE-6 FRACTION INDICATOR (YEARS)
P6N	46	A	POLE-6 HABITAT NEEDED (AREA/YEAR)
P6R	67	L	POLE-6 RESERVES (AREA)
	67.1	N	
P6S	43	R	POLE-6 SALES (AREA/YEAR)
P6SA	42	L	POLE-6 SALES ACCUMULATION (AREA)
	42.1	N	
P6VF	112	S	POLE-6 VOLUME UNITS FACTOR (VOLUME UNITS/ AREA)
P8	78	S	POLE 8-INCH HABITAT (AREA)
P8A	36	A	POLE-8 AVAILABLE (AREA/YEAR)
P8F	37.2	N	FRACTION REMOVED THROUGH POLE-8 HABITAT (PERCENT)
P8FI	37.3	N	POLE-8 FRACTION INDICATOR (YEARS)
P8N	35	A	POLE-8 HABITAT NEEDED (AREA/YEAR)
P8R	69	L	POLE-8 RESERVES (AREA)
	69.1	N	
P8S	32	R	POLE-8 SALES (AREA/YEAR)
P8SA	31	L	POLE-8 SALES ACCUMULATION (AREA)
	31.1	N	
P8VF	109	S	POLE-8 VOLUME UNITS FACTOR (VOLUME UNITS/ AREA)
RMT	9	R	REMOVE MATURE HABITAT (AREA/YEAR)
ROG	1	R	REMOVE OLD GROWTH (AREA/YEAR)
ROT	168.6	C	ROTATION SELECTED FOR RATE OF HARVEST (YEARS)
RP1	19	R	REMOVE POLE-10 HABITAT (AREA/YEAR)
RP6	41	R	REMOVE POLE-6 HABITAT (AREA/YEAR)
RP8	30	R	REMOVE POLE-8 HABITAT (AREA/YEAR)
RSA	52	R	REMOVE SAPLINGS HABITAT (AREA/YEAR)
S	4.1	C	VARIABLE STANDARD (DIMENSIONLESS)
SA	76	S	SAPLING HABITAT (AREA)
SAA	59	A	SAPLINGS AVAILABLE (AREA/YEAR)
SAF	58.2	N	FRACTION REMOVED THROUGH SAPLING HABITAT (PERCENT)
SAFI	58.3	N	SAPLING FRACTION INDICATOR (YEARS)
SAN	57	A	SAPLING HABITAT NEEDED (AREA/YEAR)
SAR	65	L	SAPLING RESERVES (AREA)
	65.1	N	
SAS	54	R	SAPLING SALES (AREA/YEAR)
SASA	53	L	SAPLING SALES ACCUMULATION (AREA)
	53.1	N	
SAVF	115	S	SAPLING VOLUME FACTOR (VOLUME UNITS)

SDO	93.1	N	STANDARD DEVIATION OPENINGS (AREA)
SDT	138	S	SQUIRREL DEN TREE INDEX (DIMENSIONLESS)
SE	63	L	SEEDLING HABITAT (AREA)
	63.1	N	
SEMT	118	S	SEDIMENT INDEX (DIMENSIONLESS)
SFMT	12	A	SALE FRACTION MATURE HABITAT (AREA/YEAR)
SFOG	4	A	SALE FRACTION OLD GROWTH (AREA/YEAR)
SFP1	22	A	SALE FRACTION POLE-10 HABITAT (AREA/YEAR)
SFP6	44	A	SALE FRACTION POLE-6 HABITAT (AREA/YEAR)
SFP8	33	A	SALE FRACTION POLE-8 HABITAT (AREA/YEAR)
SFSA	55	A	SALE FRACTION SAPLING HABITAT (AREA/YEAR)
SMT	72	R	SUCCESSION TO MATURE TIMBER (AREA/YEAR)
SO	93	S	SIZE OF OPENING (AREA)
SOF	117	S	SIZE OF OPENING FACTOR (DIMENSIONLESS)
SOG	74	R	SUCCESSION TO OLD GROWTH (AREA/YEAR)
SOM	23	A	SALE OLD GROWTH + MATURE (AREA/YEAR)
SOM1	34	A	SALE OLD GROWTH + MATURE + POLE-10 (AREA/YEAR)
SOM6	56	A	SALE OLD GROWTH + MATURE + POLE-10 + POLE-8 + POLE-6 (AREA/YEAR)
SOM8	45	A	SALE OLD GROWTH + MATURE + POLE-10 + POLE-8 (AREA/YEAR)
SPH	66	R	SUCCESSION TO POLE HABITAT (AREA/YEAR)
SP1	70	R	SUCCESSION TO POLE-10 (AREA/YEAR)
SP8	68	R	SUCCESSION TO POLE-8 (AREA/YEAR)
SQU	136	S	SQUIRREL HABITAT INDEX (DIMENSIONLESS)
SSH	64	R	SUCCESSION TO SAPLING HABITAT (AREA/YEAR)
ST	5.5	C	STANDARD VALUE OF 1 (DIMENSIONLESS)
TAH	5.2	N	TOTAL AREA ALL HABITATS (AREA)
TBBH	147.1	T	TABLE BLUEBIRD HABITAT
TBBO	148.1	T	TABLE BLUEBIRD OPENING
TBDT	129.1	T	TABLE BEAR DEN TYPE
TBHM	131.1	T	TABLE BEAR HARD MAST
TBSM	130.1	T	TABLE BEAR SOFT MAST
TDMA	135.1	T	TABLE DEER MAST AVAILABILITY
TDON	154.1	T	TABLE DOWNY WOODPECKER
TFLF	151.1	T	TABLE FLICKER FOOD
TFLN	152.1	T	TABLE FLICKER NESTING
TFLO	153.1	T	TABLE FLICKER OPENING
TGRH	143.1	T	TABLE GROUSE HABITAT
TGRO	144.1	T	TABLE GROUSE OPENINGS
THAR	159.1	T	TABLE HAIRY WOODPECKER
THS	137	S	TYPE HABITAT FOR SQUIRRELS (DIMENSIONLESS)
THTD	133.1	T	TABLE HABITAT TYPE DEER
TIM	98.1	N	TIMBER INDEX MAXIMUM (VOLUME UNITS)
TIMS	6.1	T	TABLE INDICATED TIMBER SALES
TMR	98.4	C	TIMBER MAXIMUM ROTATION AGE (YEARS)
TOFM	117.1	T	TABLE OPENING FACTOR MULTIPLIER (DIMENSIONLESS)
TOTD	134.1	T	TABLE OPENING TYPE DEER
TOVN	145.1	T	TABLE OVENBIRD
TPIL	149.1	T	TABLE PILEATED WOODPECKER
TPWE	158.1	T	TABLE PEEWEE HABITAT

TSDI	138.1	T	TABLE SQUIRREL DEN TREE
TSEMT	118.1	T	TABLE SEDIMENT INDEX
TTHS	137.1	T	TABLE TYPE HABITAT SQUIRRELS
TTRO	141.1	T	TABLE TURKEY OPENINGS
TTRT	140.1	T	TABLE TURKEY TYPE
TTWE	156.1	T	TABLE TOWHEE HABITAT
TTWO	157.1	T	TABLE TOWHEE OPENING
TTYI	98.3	T	TABLE TIMBER YIELD INDEX (VOLUME UNITS/UNIT AREA/YEAR)
TUGN	126.1	T	TABLE UGLY FOR NUMBER OF OPENINGS
TUGO	127.1	T	TABLE UGLINESS DUE TO OPENING SIZE
TUGS	125.1	T	TABLE UGLY FOR SEEDLINGS
TUR	139	S	TURKEY HABITAT INDEX (DIMENSIONLESS)
TURO	141	S	TURKEY OPENING INDEX (DIMENSIONLESS)
TURT	140	S	TURKEY TYPE HABITAT (DIMENSIONLESS)
TVBA	121.1	T	TABLE VISUAL FOR BALANCE
TVI	98	S	TIMBER VOLUME INDEX (DIMENSIONLESS)
TVM	102	S	TIMBER VOLUME MATURE TIMBER (VOLUME UNITS)
TVO	99	S	TIMBER VOLUME OLD GROWTH (VOLUME UNITS)
TVPO	123.1	T	TABLE VISUAL OLD GROWTH
TVSA	114	S	TIMBER VOLUME INDEX (VOLUME UNITS/ACRE)
TVSE	120.1	T	TABLE VISUAL DUE TO SEEDLINGS
TV1	105	S	TIMBER VOLUME POLE-10 (VOLUME UNITS)
TV6	111	S	TIMBER VOLUME POLE-6 (VOLUME UNITS)
TV8	108	S	TIMBER VOLUME POLE-8 (VOLUME UNITS)
TWE	155	S	TOWHEE HABITAT INDEX (DIMENSIONLESS)
TWH	156	S	TOWHEE HABITAT TYPE (DIMENSIONLESS)
TWO	157	S	TOWHEE OPENING TYPE (DIMENSIONLESS)
TYI	98.2	N	TIMBER YIELD INDEX (VOLUME UNITS/UNIT AREA/YEAR)
UGL	124	S	UGLINESS INDEX (DIMENSIONLESS)
UGN	126	S	UGLY DUE TO NUMBER OF OPENINGS (DIMENSIONLESS)
UGO	127	S	UGLINESS DUE TO OPENING SIZE DISTRIBUTION (DIMENSIONLESS)
UGS	125	S	UGLY DUE TO SEEDLINGS (DIMENSIONLESS)
VBAL	121	S	VISUAL APPEAL DUE TO BALANCED CONTRAST (DIMENSIONLESS)
VIS	119	S	VISUAL APPEAL INDEX (DIMENSIONLESS)
VMT	162	S	VOLUME HARVESTED MATURE TIMBER (CUBIC VOLUME)
VOG	161	S	VOLUME HARVESTED OLD GROWTH (CUBIC VOLUME)
VPCG	123	S	VISUAL DUE TO OLD GROWTH HABITATS (DIMENSIONLESS)
VP1	163	S	VOLUME HARVESTED POLE-10 (CUBIC VOLUME)
VP6	165	S	VOLUME HARVESTED POLE-6 (CUBIC VOLUME)
VP8	164	S	VOLUME HARVESTED POLE-8 (CUBIC VOLUME)
VSA	166	S	VOLUME HARVESTED SAPLINGS (CUBIC VOLUME)
VSE	120	S	VISUAL DUE TO SEEDLING HABITAT (DIMENSIONLESS)
VT	160	S	VOLUME HARVESTED TOTAL TIMBER (CUBIC VOLUME)
Y50	166.1	C	YIELD TABLE VOLUME, AGE 50 (CUBIC VOLUME)

APPENDIX C

A LISTING OF THE DYNAST-TM PROGRAM

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      *  DYNAST-TM 16 B.IVY ST
      *     OLD GROWTH LOOP
1     R  ROG.KL=OSA.K/DRT
      C  DRT=2
2     L  OSA.K=OSA.J+DT*(OGS.JK-ROG.JK)
      N  OSA=OGS
3     R  OGS.KL=SFOG.K
4     A  SFOG.K=FIFGE(LOG.K,MOG.K,COG.K,S)
      C  S=3
5     A  MOG.K=IOGS.K*FOG
      N  FOG=(TAH*OGF)/ROT
      N  TAH=ISE+ISA+IP6+IP8+IP1+IMT+IOG
      N  OGF=FIFZE(ST,NS,OGFI)
      N  OGFI=(MAX(AOG,ROT))-(MIN((AOG+DOG),ROT))
      C  ST=1
      C  NS=0
      N  AOG=AMT+DMT
6     A  IOGS.K=TABHL(TIMS,COG.K,.5,1,.1)
      T  TIMS=0/.1/.3/.5/.9/1
7     A  COG.K=OGR.K/(FOG+E)
      C  E=.01
8     A  LOG.K=MIN(OGR.K,FDH)
      N  FDH=TAH/ROT
      *     MATURE TIMBER LOOP
9     R  RMT.KL=MHA.K/DRT
10    L  MHA.K=MHA.J+DT*(MTS.JK-RMT.JK)
      N  MHA=MTS
11    R  MTS.KL=SFMT.K
12    A  SFMT.K=FIFGE(NS,MTN.K,(SFOG.K+E),FDH)
13    A  MTN.K=MIN(MTA.K,(FDH-SFOG.K))
14    A  MTA.K=FIFGE(LMT.K,MMT.K,CMT.K,S)
15    A  MMT.K=IMTS.K*FMT
      N  FMT=(TAH*MTF)/ROT
      N  MTF=FIFZE(ST,NS,MTFI)
      N  MTFI=(MAX(AMT,ROT))-(MIN(AOG,ROT))
      N  AMT=AP1+DP1
16    A  IMTS.K=TABHL(TIMS,CMT.K,.5,1,.1)
17    A  CMT.K=MTR.K/(FMT+E)
18    A  LMT.K=MIN(MTR.K,FDH)
      *     POLE-10 LOOP
19    R  RP1.KL=P1SA.K/DRT
20    L  P1SA.K=P1SA.J+DT*(P1S.JK-RP1.JK)
      N  P1SA=P1S
21    R  P1S.KL=SFP1.K
22    A  SFP1.K=FIFGE(NS,P1N.K,(SOM.K+E),FDH)
23    A  SOM.K=SFOG.K+SFMT.K
24    A  P1N.K=MIN(P1A.K,(FDH-SOM.K))
25    A  P1A.K=FIFGE(LP1.K,MP1.K,CP1.K,S)
26    A  MP1.K=IP1S.K*FP1
      N  FP1=(TAH*P1F)/ROT
      N  P1F=FIFZE(ST,NS,P1FI)
      N  P1FI=(MAX(AP1,ROT))-(MIN(AMT,ROT))
      N  AP1=AP8+DP8
27    A  IP1S.K=TABHL(TIMS,CP1.K,.5,1,.1)
28    A  CP1.K=P1R.K/(FP1+E)
29    A  LP1.K=MIN(P1R.K,FDH)
      *     POLE-8 LOOP
30    R  RP8.KL=P8SA.K/DRT
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31    L  P8SA.K=P8SA.J+DT*(P8S.JK-RP8.JK)
      N  P8SA=P8S
32    R  P8S.KL=SFP8.K
33    A  SFP8.K=FIFGE(NS,P8N.K,(SOM1.K+E),FDH)
34    A  SOM1.K=SOM.K+SFP1.K
35    A  P8N.K=MIN(P8A.K,(FDH-SOM1.K))
36    A  P8A.K=FIFGE(LP8.K,MP8.K,CP8.K,S)
37    A  MP8.K=IP8S.K*FP8
      N  FP8=(TAH*P8F)/ROT
      N  P8F=FIFZE(ST,NS,P8FI)
      N  P8FI=(MAX(AP8,ROT))-(MIN(AP1,ROT))
      N  AP8=AP6+DP6
38    A  IP8S.K=TABHL(TIMS,CP8.K,.5,1,.1)
39    A  CP8.K=P8R.K/(FP8+E)
40    A  LP8.K=MIN(P8R.K,FDH)
      *     POLE-6 LOOP
41    R  RP6.KL=P6SA.K/DRT
42    L  P6SA.K=P6SA.J+DT*(P6S.JK-RP6.JK)
      N  P6SA=P6S
43    R  P6S.KL=SFP6.K
44    A  SFP6.K=FIFGE(NS,P6N.K,(SOM8.K+E),FDH)
45    A  SOM8.K=SOM1.K+SFP8.K
46    A  P6N.K=MIN(P6A.K,(FDH-SOM8.K))
47    A  P6A.K=FIFGE(LP6.K,MP6.K,CP6.K,S)
48    A  MP6.K=IP6S.K*FP6
      N  FP6=(TAH*P6F)/ROT
      N  P6F=FIFZE(ST,NS,P6FI)
      N  P6FI=(MAX(AP6,ROT))-(MIN(AP8,ROT))
      N  AP6=ASA+DSA
49    A  IP6S.K=TABHL(TIMS,CP6.K,.5,1,.1)
50    A  CP6.K=P6R.K/(FP6+E)
51    A  LP6.K=MIN(P6R.K,FDH)
      *     SAPLING LOOP
52    R  RSA.KL=SASA.K/DRT
53    L  SASA.K=SASA.J+DT*(SAS.JK-RSA.JK)
      N  SASA=SAS
54    R  SAS.KL=SFSA.K
55    A  SFSA.K=FIFGE(NS,SAN.K,(SOM6.K+E),FDH)
56    A  SOM6.K=SOM8.K+SFP6.K
57    A  SAN.K=MIN(SAA.K,(FDH-SOM6.K))
58    A  MSA.K=ISAS.K*FSA
      N  FSA=(TAH*SAF)/ROT
      N  SAF=FIFZE(ST,NS,SAFI)
      N  SAFI=(MAX(ASA,ROT))-(MIN(AP6,ROT))
      N  ASA=DSE
59    A  SAA.K=FIFGE(LSA.K,MSA.K,CSA.K,S)
60    A  ISAS.K=TABHL(TIMS,CSA.K,.5,1,.1)
61    A  CSA.K=SAR.K/(FSA+E)
62    A  LSA.K=MIN(SAR.K,FDH)
      *     STATES OF SUCCESSION
63    L  SE.K=SE.J+DT*(ROG.JK+RMT.JK+RP1.JK+RP8.JK+RP6.JK+RSA.JK-SSH.JK)
      N  SE=ISE
64    R  SSH.KL=SE.K/DSE
65    L  SAR.K=SAR.J+DT*(SSH.JK-SAS.JK-SPH.JK)
      N  SAR=ISA
66    R  SPH.KL=SAR.K/DSA
67    L  P6R.K=P6R.J+DT*(SPH.JK-P6S.JK-SP8.JK)
      N  P6R=IP6
```

```
68    R  SP8.KL=P6R.K/DP6
69    L  P8R.K=P8R.J+DT*(SP8.JK-P8S.JK-SP1.JK)
      N  P8R=IP8
70    R  SP1.KL=P8R.K/DP8
71    L  P1R.K=P1R.J+DT*(SP1.JK-P1S.JK-SMT.JK)
      N  P1R=IP1
72    R  SMT.KL=P1R.K/DP1
73    L  MTR.K=MTR.J+DT*(SMT.JK-MTS.JK-SOG.JK)
      N  MTR=IMT
74    R  SOG.KL=MTR.K/DMT
75    L  OGR.K=OGR.J+DT*(SOG.JK-OGS.JK)
      N  OGR=IOG
      *     SUPPLEMENTARY INFORMATION
76    S  SA.K=SAR.K+SASA.K
77    S  P6.K=P6R.K+P6SA.K
78    S  P8.K=P8R.K+P8SA.K
79    S  P1.K=P1R.K+P1SA.K
80    S  MT.K=MTR.K+MHA.K
81    S  OG.K=OGR.K+OSA.K
82    S  PSE.K=SE.K/TAH
83    S  PSA.K=SA.K/TAH
84    S  PP6.K=P6.K/TAH
85    S  PP8.K=P8.K/TAH
86    S  PP1.K=P1.K/TAH
87    S  PMT.K=MT.K/TAH
88    S  POG.K=OG.K/TAH
89    S  PSEA.K=(SE.K+SA.K)/TAH
90    S  P08M.K=(P8.K+P1.K+MT.K)/TAH
91    S  P1M.K=(P1.K+MT.K)/TAH
92    S  PMO.K=(MT.K+OG.K)/TAH
93    S  SO.K=NORMRN(OPS.K,SDO)
      N  SDO=MIN(ISD,(FDH/10))
94    S  OPS.K=MIN(ISO,FDH)
95    S  NOP.K=FDH/SO.K
96    S  OPM.K=NOP.K/(TAH/640)
      *     BENEFIT AND IMPACT EQUATIONS
97    S  PTI.K=TVI.K*SOF.K
98    S  TVI.K=(TVO.K+TVM.K+TV1.K+TV8.K+TV6.K+TVSA.K)/TIM
      N  TIM=(TAH/TMR)*TYI
      N  TYI=TABHL(TTYI,TMR,20,320,30)
      T  TTYI=.41/1/1.47/1.85/1.94/1.98/2.01/2.03/2.05/2.07/2.09
      C  TMR=50
99    S  TVO.K=ROG.JK*OGVF.K
100   S  OGVF.K=TABHL(TTYI,HAOG.K,20,320,30)
101   S  HAOG.K=(OG.K/FDH)+(AOG-1)
102   S  TVM.K=RMT.JK*MTVF.K
103   S  MTVF.K=TABHL(TTYI,HAMT.K,20,320,30)
104   S  HAMT.K=(MT.K/FDH)+(AMT-1)
105   S  TV1.K=RP1.JK*P1VF.K
106   S  P1VF.K=TABHL(TTYI,HAP1.K,20,320,30)
107   S  HAP1.K=(P1.K/FDH)+(AP1-1)
108   S  TV8.K=RP8.JK*P8VF.K
109   S  P8VF.K=TABHL(TTYI,HAP8.K,20,320,30)
110   S  HAP8.K=(P8.K/FDH)+(AP8-1)
111   S  TV6.K=RP6.JK*P6VF.K
112   S  P6VF.K=TABHL(TTYI,HAP6.K,20,320,30)
113   S  HAP6.K=(P6.K/FDH)+(AP6-1)
114   S  TVSA.K=RSA.JK*SAVF.K
```

```
115     S   SAVF.K=TABHL(TTYI,HASA.K,20,320,30)
116     S   HASA.K=(SA.K/FDH)+(ASA-1)
117     S   SOF.K=TABHL(TOFM,SO.K,0,3,.5)
        T   TOFM=.5/.8/.9/.93/.95/.98/1
118     S   SEMT.K=TABHL(TSEMT,OPM.K,0,1,.2)
        T   TSEMT=0/.3/.6/.8/.9/1
119     S   VIS.K=VSE.K*VBAL.K*VPOG.K
120     S   VSE.K=TABHL(TVSE,PSE.K,.01,.07,.01)
        T   TVSE=.2/.6/.9/1/.9/.6/.2
121     S   VBAL.K=TABHL(TVBA,BAL.K,0,2,.5)
        T   TVBA=.4/.7/1/.7/.4
122     S   BAL.K=(P8.K+P1.K+MT.K)/(SE.K+SA.K+P6.K)
123     S   VPOG.K=TABHL(TVPO,POG.K,0,.7,.1)
        T   TVPO=.4/.7/.9/1/.9/.8/.6/.4
124     S   UGL.K=UGS.K*UGN.K*UGO.K
125     S   UGS.K=TABHL(TUGS,PSE.K,0,.06,.01)
        T   TUGS=0/.1/.2/.3/.5/.7/1
126     S   UGN.K=TABHL(TUGN,OPM.K,0,.8,.2)
        T   TUGN=1/.9/.7/.4/.01
127     S   UGO.K=TABHL(TUGO,OPS.K,0,30,3)
        T   TUGO=0/.50/.65/.7/.75/.8/.85/.9/.95/.97/1
128     S   BEAR.K=BDT.K*BSMT.K*BHMT.K
129     S   BDT.K=TABHL(TBDT,POG.K,0,.3,.1)
        T   TBDT=.2/.8/.9/1
130     S   BSMT.K=TABHL(TBSM,PSEA.K,0,.2,.1)
        T   TBSM=0/.5/1
131     S   BHMT.K=TABHL(TBHM,PO8M.K,0,.4,.1)
        T   TBHM=0/.2/.4/.8/1
132     S   DEER.K=HTD.K*OTD.K*DMA.K
133     S   HTD.K=TABHL(THTD,PSE.K,0,.07,.01)
        T   THTD=0/.1/.2/.5/.7/.8/.9/1
134     S   OTD.K=TABHL(TOTD,OPS.K,0,60,6)
        T   TOTD=1/1/.97/.93/.9/.85/.8/.7/.6/.5/.45
135     S   DMA.K=TABHL(TDMA,P1M.K,0,.2,.05)
        T   TDMA=.1/.2/.5/.8/1
136     S   SQU.K=THS.K*SDT.K
137     S   THS.K=TABHL(TTHS,PO8M.K,0,.4,.1)
        T   TTHS=0/.2/.4/.8/1
138     S   SDT.K=TABHL(TSDT,POG.K,0,.3,.1)
        T   TSDT=.1/.7/.8/1
139     S   TUR.K=TURT.K*TURO.K
140     S   TURT.K=TABHL(TTRT,PO8M.K,0,.5,.1)
        T   TTRT=0/.1/.2/.5/.8/1
141     S   TURO.K=TABHL(TTRO,OPS.K,0,28,2)
        T   TTRO=0/.2/.5/.7/.9/1/1/1/1/.9/.8/.7/.6/.5/.4
142     S   GRS.K=GRH.K*GRO.K
143     S   GRH.K=TABHL(TGRH,PP6.K,0,.2,.05)
        T   TGRH=0/.2/.7/.9/1
144     S   GRO.K=TABHL(TGRO,OPS.K,0,60,6)
        T   TGRO=.8/.9/.95/1/.95/.9/.85/.8/.7/.6/.5
145     S   OVN.K=TABHL(TOVN,PP6.K,0,.3,.05)
        T   TOVN=.1/.2/.4/.7/.8/.9/1
146     S   BLU.K=BBH.K*BBO.K
147     S   BBH.K=TABHL(TBBH,PSE.K,0,.06,.01)
        T   TBBH=0/.1/.2/.4/.7/.9/1
148     S   BBO.K=TABHL(TBBO,OPS.K,0,60,6)
        T   TBBO=0/.6/1/1/1/1/.95/.9/.85/.8/.7
149     S   PIL.K=TABHL(TPIL,POG.K,0,.6,.1)
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      T  TPIL=.1/.4/.6/.8/.9/.95/1
150   S  FLIC.K=FLF.K*FLN.K*FLO.K
151   S  FLF.K=TABHL(TFLF,PSE.K,0,.06,.01)
      T  TFLF=.05/.15/.3/.5/.7/.9/1
152   S  FLN.K=TABHL(TFLN,PMO.K,0,.2,.05)
      T  TFLN=.5/.8/.9/.95/1
153   S  FLO.K=TABHL(TFLO,OPS.K,0,10,2)
      T  TFLO=.05/.1/.5/.9/.95/1
154   S  DON.K=TABHL(TDON,P1M.K,0,.4,.05)
      T  TDON=.1/.15/.3/.4/.6/.8/.9/.95/1
155   S  TWE.K=TWH.K*TWO.K
156   S  TWH.K=TABHL(TTWE,PSA.K,0,.45,.05)
      T  TTWE=0/.1/.2/.4/.6/.8/.85/.9/.95/1
157   S  TWO.K=TABHL(TTWO,OPS.K,0,5,1)
      T  TTWO=.1/.5/.7/.8/.9/1
158   S  PWE.K=TABHL(TPWE,PMO.K,0,.7,.1)
      T  TPWE=.1/.2/.4/.7/.8/.9/.95/1
159   S  HAR.K=TABHL(THAR,PMO.K,0,.5,.05)
      T  THAR=.05/.1/.15/.2/.35/.5/.65/.8/.9/.95/1
160   S  VT.K=VOG.K+VMT.K+VP1.K+VP8.K+VP6.K+VSA.K
161   S  VOG.K=Y50*TVO.K*SOF.K
162   S  VMT.K=Y50*TVM.K*SOF.K
163   S  VP1.K=Y50*TV1.K*SOF.K
164   S  VP8.K=Y50*TV8.K*SOF.K
165   S  VP6.K=Y50*TV6.K*SOF.K
166   S  VSA.K=Y50*TVSA.K*SOF.K
      C  Y50=2520
      *     INVENTORY AND CONTROLS
      SPEC  DT=.25/LENGTH=170
167   A  PRTPER.K=1+STEP(39,11)
      PRINT 1)OGS,VOG/2)MTS,VMT/3)P1S,VP1/4)P8S,VP8/5)P6S,VP6/6)SAS,VSA
      PRINT 7)PTI,VT/8)OG,MT/9)P1,P8/10)P6,SA/11)SE,SEMT/12)DEER,SQU/
      PRINT 13)TUR,GRS/14)VIS,UGL
168   A  PLTPER.K=1+STEP(3,11)
      PLOT  PSE=S(0,.4)/PSA=A,PP6=6,PP8=8,PP1=1,PMT=M,POG=O,(0,.8)
      PLOT  PTI=T,SEMT=I,BEAR=B,GRS=G,TUR=K,BLU=L,DEER=D,SQU=Q(0,1)
      PLOT  VIS=V,UGL=U,OVN=O,PIL=P,FLIC=F,DON=N,TWE=W,PWE=E,HAR=H(0,1)
      C  DSE=5/DSA=30/DP6=15/DP8=15/DP1=20/DMT=35/DOG=180
      C  ISE=200/ISA=1254/IP6=1843/IP8=740/IP1=1808/IMT=366/IOG=185  B.
      C  ROT=20
      C  ISO=50/ISD=5
      RUN   20/50
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Boyce, Stephen G.
1978. Management of forests for timber and related benefits (DYNAST-TM). U. S. Dep. Agric. For. Serv., Res. Pap. SE-184, 140 p. Southeast. For. Exp. Stn., Asheville, N. C.

A technique is described for harmonizing forest management actions to provide timber as the primary product but also to provide a desirable combination of related benefits. The system is cybernetic in that it is guided toward a goal by feedback processes.

Keywords: Multiple benefit, silviculture, forest management, system dynamics, cybernetics, timber, wildlife.

The Forest Service, U. S. Department of Agriculture, is dedicated to the principle of multiple use management of the Nation's forest resources for sustained yields of wood, water, forage, wildlife, and recreation. Through forestry research, cooperation with the States and private forest owners, and management of the National Forests and National Grasslands, it strives—as directed by Congress—to provide increasingly greater service to a growing Nation.

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Southwide Tests of Carbofuran for Seedbug Control in Pine Seed Orchards

by Gary L. DeBarr

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Southeastern Forest Experiment Station
Asheville, North Carolina

Southwide Tests of Carbofuran for Seedbug Control in Pine Seed Orchards[1]

by

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Abstract.--Carbofuran (Furadan®) applied to the soil effectively controlled the pine seedbugs Leptoglossus corculus (Say) and Tetyra bipunctata (H.-S.) during 2 years of tests in 25 southern pine seed orchards owned by Federal and State governments and industry. The percentages and yields of filled seeds per cone were greatly increased with 4 oz of 10 percent carbofuran per inch of tree diameter individually applied to loblolly, slash, shortleaf, and Virginia pines. Higher but not significant mean rates of seed production occurred with increased rates of carbofuran. Two successive annual applications of carbofuran increased cone crop survival, produced the highest yields of filled seeds and reduced the variation associated with seed quality and yield per cone. Seed production was increased by 63 to 253 percent over unprotected trees. There were no significant differences among band, drill, or broadcast methods of application. Soil applications of phorate (Thimet®) did not increase seed yields.

Keywords: Phorate, Leptoglossus corculus, Tetyra bipunctata, Pinus taeda, P. elliottii var. elliottii, P. echinata, P. virginiana.

Two species of seedbugs were identified in the late sixties as potential seed chard pests (DeBarr 1967). From an economic standpoint, the leaffooted pine edbug, Leptoglossus corculus (Say), may well be the single most destructive sect found in southern pine seed orchards. Research has shown that this insect orts developing conelets, destroys immature ovules, and causes empty or maged seeds (DeBarr and Ebel 1973, 1974; DeBarr and Kormanik 1975). Anher insect, the shieldbacked pine seedbug, Tetyra bipunctata (H.-S.), also mages southern pine seeds (DeBarr 1967). However, its impact on seed proction is potentially less than that of the leaffooted pine seedbug because it feeds imarily on nearly developed seeds in maturing second-year pine cones.

In recent studies, screen-wire cages were used to compare seed quality d yield from protected and unprotected clusters of cones on loblolly pines, nus taeda L., in 15 orchards and on slash pine, P. elliottii Engelm. var. liottii, in 7 orchards (DeBarr, unpublished data). Data from these operational ed orchards demonstrated that production could be greatly increased, often ubled, by preventing seedbug feeding.

Organophosphate insecticides that had been previously field tested for control of coneworms, Dioryctria spp., also reduced seedbug damage. Trunk im-

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[1] Mention of commercial products in this Paper does not constitute endorsement by the U.S. Department of Agriculture to the exclusion of other products that may be suitable.

plants of the systemic insecticide dicrotophos (Bidrin®) significantly decrea
the percentages of seedbug-damaged seeds in collections from slash pine sta
(Merkel and DeBarr 1971). Control with soil applications of another syste
insecticide, phorate (Thimet®), was erratic. In Georgia, phorate increa
seed quality, but similar treatments in slash pine orchards in Alabama
Florida were ineffective (DeBarr and others 1972). In tests replicated in 15
lolly pine orchards of the North Carolina State Tree Improvement Cooperati
neither phorate nor a nonsystemic insecticide, stirofos (Gardona®), prever
seedbug damage.[2] When applied to control coneworms, azinphosmet
(Guthion®) provided good control of seedbugs in slash pine orchards (Merkel
others 1976) and loblolly and shortleaf pine, P. echinata Mill., orchards (DeBa
unpublished data). However, none of these insecticides was registered for se
bug control in southern pine seed orchards.

In 1974 and 1975, a standardized plan was developed by members of t
ad hoc Southern Seed Orchard Pest Committee to test the efficacy of phora
and carbofuran (Furadan®), a carbamate systemic insecticide, to control see
bugs and coneworms in southern pine seed orchards. Since phorate gave erra
control, testing was discontinued in 1975. In this study, Furadan® 10G granul
were applied at rates of 4 to 16 oz per inch of tree diameter to five species
pines growing in 25 seed orchards in 11 states. Efficacy data presented he
supported the Federal registration of carbofuran (EPA Reg. 279-2712) for see
bug control in southern pine seed orchards (DeBarr 1976).

MATERIALS AND METHODS

Test plots were located in operational seed orchards selected for use pri
marily on the basis of geographic location and a history of problems with se
insects. Because of differences in tree species, age, clones, average diamet
and height, as well as management practices, each orchard was considered t
be an individual test.

A randomized complete-block design, with clones serving as blocks, w
used in each orchard. Each orchard manager provided a list of available clone
along with ramet locations and tree diameters to the nearest 0.1 inch. T
clones and ramets for each test were selected primarily on second-year co
production and almost always had a minimum of 25 cones per tree. In mo
cases, the field layout provided a one-tree buffer between test ramets.

1974 TESTS

The 1974 tests were installed in six loblolly pine and four slash pine se
orchards (fig. 1). These tests compared the effectiveness of a single applic
tion of insecticide with multiple applications. For the multiple treatments, on
half or one-third of the material was applied initially, with one or two additio
applications in late spring or early summer (appendix table 1). At four loc
tions, the tests were also designed to compare the efficacy of phorate and ca
bofuran.

[2] DeBarr, G. L. 1976. Analysis of data from the 1973 North Carolina State Cooperative Gardon
Thimet® study. Unpublished Final Rep. FS-SE-2201-29, on file at Southeast. For. Exp. Stn., Ashevil
N. C.

Figure 1.--Locations of the 10 seed orchards in the 1974 carbofuran tests.

Each test utilized 6 clones, with 12 ramets per clone, for a total of 72 ees per orchard. The analysis of variance (ANOVA) for the standard 1974 st included five sources of variation: clones (5 df), carbofuran rates (3 df), plications (2 df), rate x application interaction (6 df), and error (55 df). The NOVA for orchards in the 1974 tests where carbofuran and phorate were com- red had nine sources of variation: clones (5 df), insecticides (1 df), insecti- de rates (2 df), applications (1 df), four interactions (7 df), and error (55 df).

Insecticide was applied to randomly selected trees at rates of 4, 8, or 16 of 10G formulation (10 percent active ingredient) per inch of tree diameter .b.h.). Phorate[3] was applied as Thimet® 10G and carbofuran[4] as Furadan® G. The granules were distributed within the soil surface area delineated by e dripline of the tree crown. A Gandy® applicator, a 1-pound coffee can with les punched in the plastic lid, or a similar device was used to distribute the anules. After treatment, the area was lightly disked or raked to incorporate e granules into the soil.

75 TESTS

Fifteen pine seed orchards were used for new tests established in 1975 g. 2). Tests were installed in nine orchards of loblolly pine, three of short-

[3] 0, 0-diethyl-S-(ethylthio) methyl phosphorodithioate.
[4] 2, 3-dihydro-2, 2-dimethyl-7-benzofuranyl methylcarbamate.

Figure 2.--Locations of the 15 seed orchards in the 1975 carbofuran tests.

leaf pine, two of slash pine, and one of Virginia pine, P. virginiana Mill. (a pendix table 2). Carbofuran was tested in single applications at rates of 4, and 12 or 16 oz of Furadan® 10G per inch of tree diameter.

The basic design called for 6 clones, with 4 or 8 ramets per clone, o total of either 24 or 48 trees per orchard. However, at several locations or 4 or 5 suitable clones were available, and in one orchard 9 clones were us The ANOVA for the standard 1975 test had three sources of variation: clo (5 df), carbofuran rates (3 df), and error (15 df).

All applications were completed during a 3-week period from February to March 3, 1975. The granules were broadcast and incorporated as in previ tests.

SPECIAL TESTS

Two additional field tests were installed in 1975 specifically to evalu formulations and application methods. W. W. Neel[5] designed a test to compa three patterns of distribution of granular carbofuran under individual trees:

Band.--Carbofuran was applied in circular bands, 24 inches wide, just side the periphery of the dripline of each tree. Weeds and grasses were clea

[5] Department of Entomology, Mississippi Agricultural and Forestry Experiment Station, Miss sippi State University, Mississippi State, Miss. 39762.

om the strips before insecticide application. Soil was lightly disked, and ranules were incorporated with a rake.

Drill.--Carbofuran was placed in six small auger holes (2 to 3 inches eep) spaced uniformly along the dripline of the trees.

Broadcast.--Carbofuran granules were broadcast uniformly under the own of each tree. Ground vegetative cover was not removed or killed.

Neel's study was conducted in a slash pine orchard near Leakesville, issisippi. The trees had been grafted in 1962 and 1963 and represented five ones. One ramet from each clone was randomly selected for each treatment. arbofuran was applied at annual rates of 8 or 16 oz of Furadan® 10G per inch tree diameter. Split applications of the insecticides were made in April and ne 1974 and in April and June 1975.

Another test, established by W. C. Yearian,[6] compared Furadan® 4 Flowle with the Furadan® 10G formulation used for the 1974-1975 tests. In a loblly pine seed orchard near Pine Bluff, Arkansas, the insecticide was poured er the soil surface within the projection of the crown of each tree at rates uivalent to 4, 8, and 16 oz of Furadan® 10G per inch of diameter. The trees eraged 10 years of age, 7.5 inches d.b.h., and 30 feet in height.

VALUATION OF SEEDBUG CONTROL

Cone Survival

In loblolly pine orchards near Cochran and Greensboro, Georgia, and in a ash pine orchard at Rincon, Georgia, six sample branches were selected and gged on each test tree. The numbers of healthy conelets on the branches were corded in the early spring of 1974; then, just prior to cone harvest in the fall 1975, the counts were repeated.

Cone Handling and Seed Radiography

Each fall the mature cone crop was harvested from the individual test ees. From each tree, six sound cones, each apparently healthy and free of echanical injury or cone insect damage, were placed in a Kraft paper bag and ipped to Athens, Georgia, or Raleigh, North Carolina, where the cones were ied and the seeds extracted.

All extracted seeds were radiographed at the Forestry Sciences Laboratory, Athens, Georgia. To save time, preserve sample integrity, and prevent e loss of partially empty seed, the samples were not dewinged or cleaned but ere placed directly into 3- by $5\frac{1}{2}$-inch paper envelopes. Each envelope conining seeds from six cones was taped onto the paper used to protect the X-ray lm in Kodak Redipacks® (fig. 3A). To prevent superimposed images on the adiograph, the seeds were gently pressed into a single layer. Each 14- by 17-ch Redipack® accommodated 12 envelopes and served as a reference to the lo-

[6] Department of Entomology, Virology & Biocontrol Laboratory, University of Arkansas, University Farm, Route 6, Fayetteville, Ark. 72701.

cation of the samples on the processed radiograph (fig. 3B). Numbering ... samples also minimized bias during the interpretation of the radiographs.

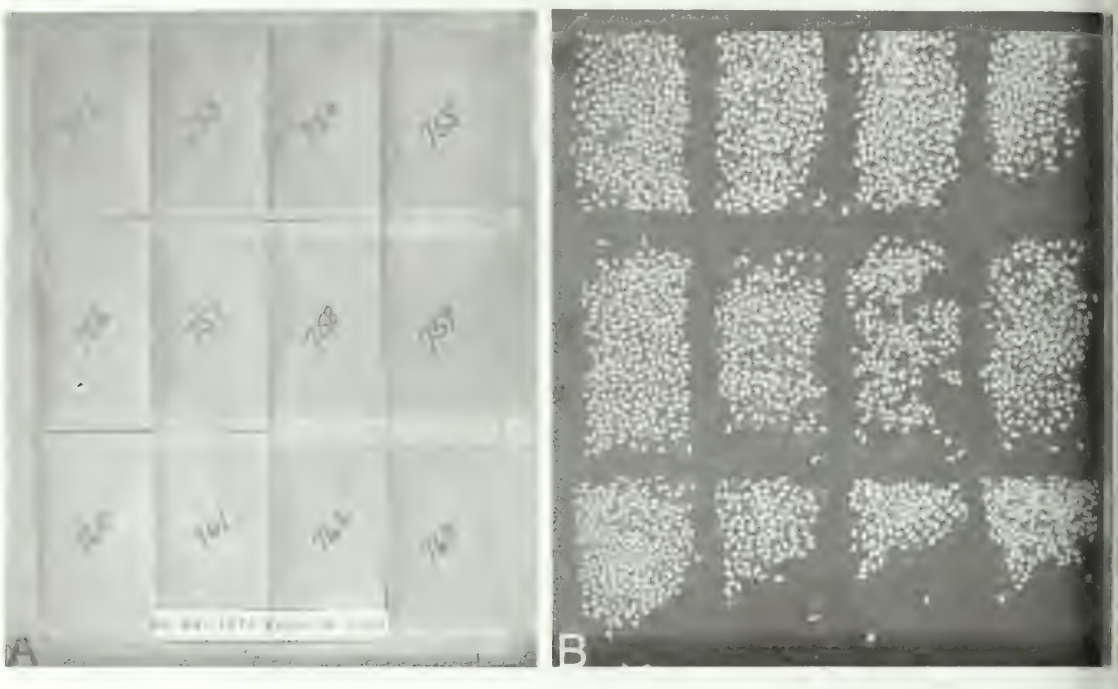

Figure 3.--Seed samples from individual test trees were enclosed in envelopes and ta onto Kodak Redipack® X-ray film (A). Radiograph of the individual samples (B).

The X-ray film was exposed and the radiographs were evaluated accord to procedures previously reported by DeBarr (1970, 1974a). On the rad graphs, the seeds were classed as filled, seedbug-damaged (which inclu second-year aborted ovules), or empty. All seeds not readily classified filled or seedbug-damaged were counted in the "empty" category. This categ included seeds with the contents destroyed by seedworms, Laspeyresia sp such seeds were easily identified but rarely found, averaging less than 0.1 cone.

Radiographic data were used to calculate parameters of seed qua (mean percentages of filled, empty, and seedbug-damaged seeds per cone) yield (mean numbers of total seeds and filled seeds per cone). Data from e individual orchard were subjected to an analysis of variance. Percentage d were transformed to arcsin$\sqrt{\text{percent}}$ prior to analysis. Duncan's new multi range test was used to determine statistically significant differences am treatment means.

RESULTS AND DISCUSSION

1974 TESTS

Loblolly Pine Orchards

Carbofuran consistently controlled pine seedbugs in the loblolly pine chards at Cochran and Greensboro, Georgia; Lumberton, North Carolina;

New Kent, Virginia (appendix tables 3 and 4). Treated trees had significantly higher percentages of filled seeds than did the controls. The amount of damaged seeds detected on the radiographs was also significantly less for all the carbofuran treatments.

In addition, seed yields per cone dramatically increased. In every comparison between protected and unprotected trees at Cochran and Greensboro, Georgia, and New Kent, Virginia, the number of seeds per cone was significantly increased. However, at Lumberton, North Carolina, only the single application of 8 oz significantly increased seeds per cone. All the carbofuran treatments except one (4 oz applied in a single dose at Lumberton) produced significant increases in filled seeds per cone, ranging from 107 to 312 percent.

The level of seedbug activity in the individual orchards limited the potential for improved seed production. In the orchards at Pine Bluff, Arkansas, and Washington, North Carolina, seedbug damage was so low that the effectiveness of carbofuran could not be evaluated. For example, cones from the unprotected trees at Washington, North Carolina, produced 86 filled seeds per cone, the highest yields for any orchard in the 1974 tests; an average of 88 percent of the total seeds extracted were filled.

Slash Pine Orchards

Trees protected with carbofuran produced higher quality seeds in three of the four slash pine orchards during 1974. All the carbofuran treatments at Leakesville, Mississippi, and Rincon and Woodbine, Georgia, resulted in significantly higher percentages of filled seed than the check trees (appendix tables 3 and 4; 1974 data on Leakesville appear in a subsequent section). Damaged seeds detected on the radiographs were significantly less for all the treatments except one (4 oz applied as a single dose at Woodbine). Some of the treatments increased the total number of seeds per cone, while almost all the protected trees yielded significantly more filled seeds per cone than the unprotected trees.

Carbofuran failed to control seedbugs at the Magnolia Springs, Texas, orchard, where the amount of late-summer damage detected was not significantly reduced by any of the carbofuran treatments. Some of this damage may have resulted from poor control of shieldbacked pine seedbugs, which, because of differences in feeding behavior or tolerance to carbofuran, were not affected by the treatments.

Comparisons of Insecticides, Applications, and Rates

In contrast to carbofuran, no phorate treatment significantly increased the number of filled seeds per cone over yields from the check trees in any of the four orchards where these insecticides were compared (appendix table 4). However, radiographs of seeds protected with the highest rates of phorate at Greensboro and Rincon, Georgia, showed significantly fewer damaged seeds, indicating some late-summer control of seedbugs.

Comparisons of single versus multiple applications of carbofuran within each rate (4, 8, or 16 oz per inch d.b.h.) showed no significant differences in

yields of filled seeds per cone, with a single exception at Cochran, Georg
(appendix tables 3 and 4). Thus, a single application of carbofuran in April w
as effective as dividing the insecticide and applying it on two or three applic
tion dates.

Single applications at the 8- or 16-oz rate did not significantly increa
yields of filled seeds per cone over those from trees protected at the 4-oz rat
with one exception at Lumberton, North Carolina (appendix tables 3 and 4
The additional seeds produced by doubling or quadrupling the amount of carb
furan were insufficient to justify the increased insecticide cost and pesticid
load in the orchard.

1975 TESTS

Loblolly Pine Orchards

Unprotected trees in the eight loblolly pine orchards used for the 19
tests yielded high-quality seeds (appendix table 5). As evidenced by damag
seeds detected on radiographs, the destruction caused by late-summer feedi
of seedbugs was less than 10 percent in all the orchards, except Moncks Corne
South Carolina, where it was only slightly higher (10.8 percent). Damage av
eraged less than 2 percent at Natchez, Mississippi; Rock Hill, South Carolin
and New Kent, Virginia. All the carbofuran treatments significantly reduc
damage at Aliceville, Alabama, and Georgetown, South Carolina, but only the
and 12-oz rates were effective at Hodge, Louisiana, and Moncks Corner, Sou
Carolina. At Conroe, Texas, none of the carbofuran treatments reduced th
amount of damaged seeds below the 4.5 percent level found in the check sampl
Only at Georgetown, South Carolina, and Hodge, Louisiana, did carbofuran at
12-oz rate significantly increase the percentage of filled seeds.

Unprotected trees also had better seed yields in 1975 than in 1974. Ca
bofuran significantly increased the number of seeds per cone only at Hodg
Louisiana (12-oz rate), Rock Hill, South Carolina (8-oz rate), and New Ken
Virginia (4-, 8-, and 16-oz rates). At these sites and at Georgetown, Sou
Carolina, protected cones had significantly more filled seed; however, the yiel
did not differ among rates. Cones from check trees at Aliceville, Alabama, a
eraged 110 filled seed, while those from Natchez, Mississippi, averaged 9
these high yields precluded any substantial improvements. Carbofuran failed
increase significantly the yields of filled seeds per cone at Rock Hill, Sou
Carolina, and Conroe, Texas.

At New Kent, Virginia, seed qualities and yields were similar for loblol
pines treated at the 8-oz rate in either February or April. However, only th
February application produced significantly more filled seeds per cone than th
unprotected trees.

Seedbug feeding in the test orchards was much less in 1975 than in 197
Furthermore, exceptionally good cone crops in most of the loblolly pine or
chards in 1975 probably lessened the impact of the insects on individual cone
Consequently, the potential for demonstrating improved seed production wit
carbofuran was much less than it had been in 1974.

Shortleaf Pine Orchards

Carbofuran was applied to shortleaf pines for the first time in 1975 (appendix table 5). All three rates tested at Pollock, Louisiana, and the 8- and 12-z rates at Springhill, Louisiana, significantly improved the percentages of lled seeds. At Springhill, late-summer damage was significantly less for all reatments than that observed on the check trees, but at Pollock only the 12-oz reatment was effective. At Pollock, trees protected with 8 and 12 oz of carbo-uran also produced more seeds per cone. At both orchards, all three rates ignificantly increased the yields of filled seeds above those from the check trees.

Seedbugs almost totally destroyed the seed crop on unprotected ramets at ollock. Despite increases of 300 to 425 percent in filled seeds per cone, the arbofuran-protected trees still sustained considerable seed losses. While it ppears that the carbofuran treatments were less effective under pressures rom heavy seedbug populations, it also seems likely that much of this damage esulted from a continued influx of insects into the individual test trees from ie vast number of untreated trees in the orchard.

No seedbug activity was observed at Idabel, Oklahoma, and, therefore, ie effectiveness of carbofuran could not be evaluated.

Slash Pine Orchards

Two new tests were established in slash pine orchards in 1975. Only at eakesville, Mississippi, did the carbofuran treatments (8 and 16 oz) signifi-antly increase the percentages of filled seeds (appendix table 5). Late-summer amage by seedbugs as found on the radiographs was significantly reduced by all ie treatments at Magnolia Springs, Texas, but not at Leakesville. Significant-more filled seeds per cone were produced by protected trees at both orchards. ones from trees treated with the highest rates of carbofuran averaged more an 100 filled seeds.

Virginia Pine Orchard

Seedbug activity was relatively light at the only orchard of Virginia pine ncluded in the 1975 tests (appendix table 5). All three carbofuran treatments esulted in significantly lower percentages of damaged seed at this orchard in efferson County, Tennessee. These responses, however, were too small to ause significant improvements in yields of filled seeds.

PECIAL TESTS

Applications of granular and flowable formulations of carbofuran were ompared at Pine Bluff, Arkansas, but seedbug damage was so low that differ-nces in effectiveness could not be demonstrated (appendix table 6). These data ere highly variable, and even large differences in yields were not statistically gnificant.

In the Leakesville, Mississippi, orchard where carbofuran was distributed three different patterns under slash pine trees, protected cones showed sig-ificant improvements in seed quality (appendix table 7). In 1974 only the drill

method of application failed to improve yields. After 2 years of protection, th drill and broadcast treatments significantly improved yields, but the bandin method did not. Although only the broadcast method significantly improv yields in both years, there were no significant differences in yield among th three methods, and none could be considered superior to the others.

CONE SURVIVAL

Survival of the cone crop on 59 trees was tallied in three orchards (ap pendix table 8). In the loblolly pine orchard at Cochran, Georgia, 81 percent the conelets initially present on the check trees were collected as matu healthy cones. Single applications of carbofuran at the 16-oz rate increas cone survival to 99 percent. At Greensboro, Georgia, this same treatment in creased survival to 97 percent in comparison with only 76 percent survival o unprotected trees. In the slash pine orchard at Rincon, Georgia, survival av eraged only 16 percent on the check trees, while 87 percent of the crop wa harvested on trees protected with 16 oz of carbofuran.

Although specific causes were not identified, most of the increased sur vival resulted from reduced conelet losses, particularly from a reduction conelet abortion. Since feeding by the leaffooted pine seedbug induces conel abortion (DeBarr and Ebel 1973, 1974), it seems likely that carbofuran af forded some protection to the conelets. Without the use of tagged samples t develop crop life tables, however, conelet losses usually go undetected (DeBa and Barber 1975).

1974 TEST ORCHARDS NOT RE-TREATED IN 1975

Cone samples were collected from trees in two orchards which had be treated in 1974 but left untreated in 1975. Conelets protected with the high rates of carbofuran in 1974 during their first year of seed development and ha vested as cones in 1975 yielded from 47 to 109 percent more filled seeds th cones from unprotected trees (appendix table 9). While there were also son reductions in the percentages of empty and seedbug-damaged seeds, the in proved yields were due almost entirely to more seeds per cone. Such increas in seeds per cone generally reflect reductions in ovule abortion (DeBarr a Ebel 1973; DeBarr and others 1975); thus, carbofuran apparently controll seedbug feeding on conelets and immature cones in the two orchards.

1974 TEST ORCHARDS RE-TREATED IN 1975

In four of the 1974 test orchards, single applications of carbofuran we reapplied to the same trees during 1975. Losses at Washington, North Car lina, were minor for both years, but results from the other orchards demo strated the value of using carbofuran to protect cone crops from seedbu through both growing seasons. In treated trees in these three orchards, se production was 63 to 253 percent higher than in unprotected trees (append table 10).

In the Lumberton, North Carolina, loblolly pine orchard, two annual a plications of 4 or 8 oz of carbofuran per inch of diameter increased filled se

elds by 209 and 253 percent. Unprotected cones produced only 32 filled seeds, hile those treated at the 4-oz rate averaged 99 filled seeds. The 8-oz treatent yielded 113 filled seeds per cone, and cones from one tree protected with e 8-oz rate averaged 161 filled seeds. These same two rates increased filled eds by 63 percent at the loblolly pine orchard in New Kent, Virginia.

At the slash pine orchard in Rincon, Georgia, the two annual applications carbofuran increased seed production by 134 to 186 percent over the 35 filled eds per cone harvested from unprotected trees. The 4-oz rate increased the erage yield of filled seeds to 82. Cones protected at the 8-oz rate yielded 97 led seeds, while those protected at the 16-oz rate yielded 100 filled seeds. nes from one tree protected at the 16-oz rate averaged 151 filled seeds.

As shown in appendix table 10, the variation associated with the percente of filled, empty, or seedbug-damaged seeds (as well as the number of total filled seeds per cone) diminished with increased rates of carbofuran. As esnators for the efficacy of carbofuran in reducing seed losses caused by seedgs, these parameters differ in their relative usefulness (Bramlett and others 77; DeBarr 1974a, 1974b). Although counts of damaged seeds from radioaphs offer the best direct measurement of insect feeding, such counts often derestimate the total impact of seedbugs. Ideally, insecticides (such as carfuran) which control seedbugs should minimize conelet and ovule abortion, as ell as reduce the numbers of empty and damaged seeds. Effective control will reflected by an increase in cone crop survival, total seeds per cone, perntage of filled seeds per cone, and ultimately, an increase in the yield of led seeds per cone. At the same time, the variation associated with these rameters will be reduced.

CONCLUSIONS

1. In comparative tests, ramets protected with carbofuran produced a gher number and higher percentage of filled seeds per cone than did check ees, while phorate did not increase seed production.

2. Carbofuran treatments often doubled the yield of filled seeds per cone, en when the cones were protected only during the second year of development.

3. Seedbug control was as good when all the carbofuran was applied at one ne as when the material was divided among two or three application dates.

4. Rates above 4 oz of 10 percent carbofuran per inch of tree diameter nerally increased the number of filled seeds per cone, but the increments re too small to be statistically significant.

5. A single annual application of carbofuran enhanced seed yields the folg year, apparently by reducing ovule abortion in protected conelets, but there s little or no carryover in direct control of seedbugs.

6. Two successive annual applications of carbofuran provided the highest elds of filled seeds, increased the survival of the cone crops, and reduced the riation associated with seed quality and yield per cone.

7. There were no significant differences among band, drill, or broadca methods of application.

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Appendix

(Appendix tables 1 through 10)

Table 1.--Orchard location, tree characteristics, test size, and application dates for the 1974 carbofuran tests

Map No.[1]	Species and orchard location	Ramet		Clones	Test trees				Application dates[2]		
		Age	D.b.h.		Carbofuran	Phorate	Check	Orchard total			
		Years	Inches	No.	- - - - - - - - - No. - - - - - - - - -						
	Loblolly pine										
1	Pine Bluff, Ark.	10	7.5	6	54	--	18	72	3/21	5/29	6/26
2	Cochran, Ga.	10	7.8	6	54	--	18	72	4/4	6/6	7/23
3	Greensboro, Ga.	8	5.7	4	24	12	12	48	3/28	5/28	7/1
4	Lumberton, N. C.	15	12.8	6	24	24	24	72	4/15	6/17	7/23
5	Washington, N. C.	15	12.0	6	24	24	24	72	4/1	6/1	7/1
6	New Kent, Va.	12	10.0	9	68	--	17	85	4/1	5/15	6/14
	Slash pine										
7	Rincon, Ga.	10	8.0	5	30	30	20	80	3/21	5/14	6/15
8	Woodbine, Ga.	19	13.0	6	18	--	6	24	4/17	6/18	--
9	Leakesville, Miss.	7	6.5	5	20	--	12	32	4/7	6/6	--
10	Magnolia Springs, Tex.	12	11.5	6	54	--	18	72	5/13	6/15	7/16

[1] Numbers refer to locations of seed orchards in figure 1.

[2] Single applications made on the first date only; double applications made on the first and second dates; triple applications made on all three dates.

Table 2.--Orchard locations, tree characteristics, test size, and application dates for the 1975 carbofuran tests

Map No.[1]	Species and orchard location	Ramet		Clones	Test trees			Application date
		Age	D.b.h.		Carbofuran	Check	Orchard total	
		Years	Inches	No.	----- No. -----			
	Loblolly pine							
1	Pine Bluff, Ark.	11	--	5	30	5	35	2/28
2	Aliceville, Ala.	--	6	6	36	12	48	2/12
3	Hodge, La.	10	9-14	6	18	6	24	2/21
4	Natchez, Miss.	13	12	6	36	12	48	2/19
5	Georgetown, S. C.	--	14	6	36	12	48	2/19
6	Moncks Corner, S. C.	--	6	6	18	6	24	2/19
7	Rock Hill, S. C.	12	9-14	5	30	10	40	2/12
8	Conroe, Tex.	--	--	6	18	6	24	2/27
9	New Kent, Va.	10	10	6	36	12	48	2/20
	Shortleaf pine							
10	Pollock, La.	--	--	6	18	6	24	2/10
11	Springhill, La.	--	5-11	6	18	6	24	2/12
12	Idabel, Okla.	7	4	6	18	6	24	2/18
	Slash pine							
13	Leakesville, Miss.	7	6-7	6	18	6	24	3/3
14	Magnolia Springs, Tex.	12	12	6	18	6	24	3/3
	Virginia pine							
15	Jefferson County, Tenn.	--	6	9	27	9	38	2/21

[1] Numbers refer to locations of seed orchards in figure 2.

Table 3.--Average seed quality and yield per cone for trees protected with carbofuran at varying rates and applications, 1974

Orchard location and species	Carbofuran rate		Seed quality[1]			Seed yields		
	10G/inch d.b.h.	Applications[2]	Filled	Empty	Seedbug-damaged	Seeds/cone	Filled seeds/cone	Increase in filled seeds/cone[3]
	Oz	No.	- - - Percent[4] - - -			- - No.[4] - -		Percent
Pine Bluff, Ark.								
Loblolly pine	0	0	85.8a	12.5a	1.7a	72a	62a	--
	4	1	87.6a	12.0a	.4a	67a	59a	--
	8	1	85.4a	14.0a	.6a	61a	52a	--
	16	1	88.6a	10.7a	.7a	72a	64a	--
	4	2	84.2a	14.0a	1.8a	65a	55a	--
	8	2	88.6a	11.0a	.4a	71a	63a	--
	16	2	89.2a	10.4a	.4a	76a	68a	--
	4	3	88.5a	11.1a	.4a	67a	59a	--
	8	3	87.6a	11.1a	1.3a	73a	64a	--
	16	3	85.8a	12.7a	1.5a	76a	65a	--
Cochran, Ga.								
Loblolly pine	0	0	50.0a	21.5a	28.5a	33a	17a	--
	4	1	77.5b	19.8ab	2.7b	61bcd	47bc	176
	8	1	85.3b	13.1b	1.6b	82d	70c	312
	16	1	86.9b	12.5b	.6b	79cd	69c	306
	4	2	89.0b	10.2b	.8b	61bcd	54bc	218
	8	2	86.8b	11.9b	1.3b	75cd	65c	282
	16	2	81.9b	15.1ab	3.0b	61bcd	50bc	194
	4	3	76.4b	18.2ab	5.4b	54bc	41b	141
	8	3	86.2b	11.6b	2.2b	45b	39b	129
	16	3	84.9b	14.2b	.9b	72cd	61bc	259
New Kent, Va.								
Loblolly pine	0	0	36.5a	44.4a	19.1a	31a	11a	--
	8	1	72.3b	25.2b	2.5b	42b	30b	172
	16	1	77.1b	21.6b	1.3b	45b	35b	218
	8	3	76.9b	21.2b	1.9b	50b	38b	245
	16	3	75.7b	22.1b	2.2b	44b	33b	200
Woodbine, Ga.								
Slash pine	0	0	63.2a	28.4a	8.4a	29a	18a	--
	4	1	79.9b	15.9b	4.2ab	53b	42b	133
	8	1	84.5b	13.3b	2.2b	30a	25ac	--
	16	1	87.4b	11.0b	1.6b	41ab	36bc	100
Magnolia Springs, Tex.								
Slash pine	0	0	60.9a	17.7a	21.4a	28a	17a	--
	4	1	82.5a	12.3a	5.2a	31a	26a	--
	8	1	66.2a	19.1a	14.7a	20a	13a	--
	16	1	79.9a	13.0a	7.1a	30a	24a	--
	4	2	67.7a	21.8a	10.5a	17a	12a	--
	8	2	79.5a	15.2a	5.3a	26a	21a	--
	16	2	75.8a	15.4a	8.8a	25a	19a	--
	4	3	73.3a	17.1a	9.6a	25a	18a	--
	8	3	76.1a	12.9a	11.0a	22a	17a	--
	16	3	82.6a	14.1a	3.3a	32a	26a	--

[1] By radiographic analysis.
[2] Number of applications administered to obtain indicated dosage.
[3] Calculated only when treatment mean differed significantly from check mean.
[4] For each seed orchard, any two means (within a column) followed by the same letter are not significantly different at the 5 percent level by Duncan's new multiple range test.

Table 4.--Average seed quality and yield per cone for trees protected with carbofuran and phorate at varying rates and applications, 1974

Orchard location, species, and insecticide	Insecticide rate		Seed quality[1]			Seed yields		
	10G/inch d.b.h.	Applications[2]	Filled	Empty	Seedbug-damaged	Seeds/cone	Filled seeds/cone	Increase in filled seeds/cone[3]
	Oz	No.	----Percent[4]----			--No.[4]--		Percent
Greensboro, Ga.								
Loblolly pine	0	0	48.6a	31.3a	20.1a	45a	22a	--
Carbofuran	4	1	77.9bc	18.3b	3.8b	92b	72b	227
	8	1	85.7bc	12.7b	1.5b	86b	74b	236
	16	1	88.7c	10.9b	.4b	75b	67b	205
	4	3	86.3bc	12.0b	1.7b	84b	72b	232
	8	3	88.2c	11.0b	.8b	92b	81b	268
	16	3	85.8bc	12.9b	1.3b	95b	82b	272
Phorate	4	1	58.4a	27.1a	14.5a	47a	27a	--
	8	1	65.5b	25.8a	8.7a	69a	45a	--
	16	1	78.4bc	16.3b	5.3b	57a	45a	--
Lumberton, N. C.								
Loblolly pine	0	0	48.8a	33.4a	17.8a	60a	29a	--
Carbofuran	4	1	84.3b	13.3b	2.4b	52a	44ab	--
	8	1	85.5b	12.8b	1.7b	86b	74c	155
	4	3	83.5b	15.2b	1.3b	72ab	60bc	107
	8	3	85.0b	13.6b	1.4b	73ab	62bc	114
Phorate	4	1	58.9a	25.2a	15.9a	64a	38a	--
	8	1	58.6a	22.5a	18.9a	66a	39a	--
	4	3	45.8a	24.2a	30.0c	57a	26a	--
	8	3	53.1a	28.3a	18.6a	51a	27a	--
Washington, N. C.								
Loblolly pine	0	0	88.1a	8.0a	3.8a	98a	86a	--
Carbofuran	4	1	86.7a	10.4a	2.9a	98a	85a	--
	8	1	86.0a	11.5a	2.4a	97a	83a	--
	4	3	82.5a	14.3a	3.2a	99a	82a	--
	8	3	87.6a	10.4a	2.1a	104a	91a	--
Phorate	4	1	92.7a	5.8a	1.5a	111a	103a	--
	8	1	87.0a	8.4a	4.6a	112a	97a	--
	4	3	88.1a	10.6a	1.2a	95a	84a	--
	8	3	87.7a	9.2a	3.1a	107a	94a	--
Rincon, Ga.								
Slash pine	0	0	52.1a	37.0a	10.9a	24a	13a	--
Carbofuran	4	1	76.1bc	22.2b	1.7b	40ab	30bc	131
	8	1	81.1c	17.0b	1.9b	38ab	31bc	138
	16	1	82.3c	15.8b	1.9b	50b	41c	215
	4	3	72.6b	22.1b	5.3b	32ab	23ab	--
	8	3	80.9c	17.5b	1.6b	49b	40bc	208
	16	3	81.4c	17.6b	1.0b	56b	46c	254
Phorate	4	1	60.5a	33.4a	6.1b	36a	22a	--
	8	1	59.4a	35.5a	5.1b	35a	21a	--
	16	1	63.1a	31.7a	5.2b	35a	22a	--
	4	3	44.9a	35.1a	20.0c	40a	18a	--
	8	3	65.1a	26.5a	8.4a	37a	24a	--
	16	3	62.2a	31.9a	5.9b	34a	21a	--
Azinphosmethyl[5]			68.9	25.1	6.0	47	32	146

[1] By radiographic analysis.
[2] Number of applications administered to obtain indicated dosage.
[3] Calculated only when treatment mean differed significantly from check mean.
[4] For each seed orchard, any two means (within a column) followed by the same letter are not significantly different at the 5 percent level by Duncan's new multiple range test.
[5] Operational azinphosmethyl (Guthion®) spray schedule.

Table 5.--Average seed quality and yield per cone for trees protected with single applications of carbofuran, 1975

Orchard location and species	Carbofuran rate	Seed quality[1]			Seed yields		
	10G/inch d.b.h.	Filled	Empty	Seedbug-damaged	Seeds/ cone	Filled seeds/ cone	Increase in filled seeds/ cone[2]
	Oz	----- Percent[3] -----			-- No.[3] --		Percent
Aliceville, Ala.							
Loblolly pine	0	91.3a	6.4a	2.3a	118a	110a	--
	4	95.4b	4.2a	.4b	139a	133a	--
	8	94.4ab	5.2a	.4b	127a	120a	--
	16	93.9ab	6.0a	.1b	110a	103a	--
Hodge, La.							
Loblolly pine	0	67.4a	28.6a	4.0a	74a	50a	--
	4	72.3ab	25.0ab	2.7ab	93ab	67b	34
	8	76.5ab	22.1ab	1.4b	88ab	67b	34
	12	79.2b	19.7b	1.1b	99b	78b	56
	Guthion[4]	75.6	22.2	2.2	98	74	48
Natchez, Miss.							
Loblolly pine	0	83.8a	14.6a	1.6a	115a	96a	--
	4	78.8a	19.3a	1.9a	121a	95a	--
	8	85.9a	13.0a	1.1a	121a	104a	--
	12	85.6a	13.3a	1.1a	125a	107a	--
	Guthion[4]	85.7	12.6	1.7	95.8	81.7	--
Georgetown, S. C.							
Loblolly pine	0	70.3a	20.8a	8.9a	111a	77a	--
	4	86.1b	11.6b	2.3b	109a	94b	22
	8	85.5b	13.7b	.8b	110a	94b	22
	16	90.5b	9.0b	.5b	118a	107b	39
Moncks Corner, S. C.							
Loblolly pine	0	66.0a	23.2a	10.8a	85a	56a	--
	4	74.0a	23.3a	2.7ab	70a	52a	--
	8	78.9a	20.7a	.4b	77a	61a	--
	12	79.8a	19.4a	.8ab	80a	64a	--
Rock Hill, S. C.							
Loblolly pine	0	75.7a	22.7a	1.6a	78a	59ab	--
	4	72.1a	26.5a	1.4a	76a	55a	--
	8	73.9a	24.7a	1.4a	97b	72b	--
	16	73.2a	25.5a	1.3a	86ab	63ab	--
Conroe, Tex.							
Loblolly pine	0	71.9a	23.6a	4.5a	83a	60a	--
	4	67.3a	26.0a	6.7a	88a	59a	--
	8	77.2a	17.9a	4.9a	76a	59a	--
	12	68.3a	26.9a	4.8a	78a	53a	--

(continued)

Table 5.--Average seed quality and yield per cone for trees protected with single applications of carbofuran, 1975 (continued)

Orchard location and species	Carbofuran rate	Seed quality[1]			Seed yields		
	10G/inch d.b.h.	Filled	Empty	Seedbug-damaged	Seeds/ cone	Filled seeds/ cone	Increase in filled seeds/ cone[2]
	Oz	Percent[3]			No.[3]		Percent
New Kent, Va.							
Loblolly pine	0	80.6a	17.5a	1.9a	73a	59a	--
	4	85.0a	13.5a	1.5a	81b	67b	14
	(Feb.) 8	83.9a	15.0a	1.1a	80b	67b	14
	(Apr.) 8	84.2a	14.7a	1.1a	78ab	66ab	--
	16	82.1a	17.6a	.3a	85b	70b	9
Pollock, La.							
Shortleaf pine	0	11.0a	60.2a	28.8a	33a	4a	--
	4	38.1b	42.4b	19.5ab	43ab	16b	300
	8	46.8b	38.7b	14.5ab	44b	21b	425
	12	47.3b	42.7b	10.0b	38b	18b	350
Springhill, La.							
Shortleaf pine	0	56.1a	33.9a	10.0a	85a	48a	--
	4	71.7b	26.1ab	2.2b	85a	61b	27
	8	73.6b	23.3b	3.1b	91a	67b	40
	12	76.5b	23.1b	.4b	85a	65b	35
Idabel, Okla.							
Shortleaf pine	0	77.6a	22.2a	.2a	61a	47a	--
	4	74.3a	25.0a	.7a	64a	48a	--
	8	77.3a	22.6a	.1a	64a	49a	--
	16	78.9a	20.9a	.2a	60a	47a	--
Leakesville, Miss.							
Slash pine	0	77.2a	18.4a	4.4a	115a	89a	--
	4	77.4a	17.3a	5.3a	137b	106b	19
	8	86.8b	11.5a	1.7a	126ab	109b	22
	16	87.0b	11.8a	1.2a	129ab	112b	26
Magnolia Springs, Tex.							
Slash pine	0	73.7a	18.2a	8.1a	100a	74a	--
	4	80.2a	17.6a	2.2b	96a	77a	--
	8	85.1a	11.4a	3.5b	120ab	102b	38
	12	80.5a	17.6a	1.9b	135b	109b	47
	Guthion[4]	82.4	15.3	2.3	96	79	--
Jefferson County, Tenn.							
Virginia pine	0	76.8a	18.9a	4.3a	51a	39a	--
	4	88.8b	10.5b	.7b	56a	49a	--
	8	83.8ab	14.7ab	1.5b	49a	41a	--
	16	81.6ab	16.7ab	1.7b	47a	38a	--

[1] By radiographic analysis.
[2] Calculated only when treatment mean differed significantly from check mean.
[3] For each seed orchard, any two means (within a column) followed by the same letter are not significantly different at the 5 percent level by Duncan's new multiple range test.
[4] Operational azinphosmethyl (Guthion®) spray schedule.

Table 6.--Average seed quality and yield per cone for loblolly pine trees protected with liquid or granular carbofuran at Pine Bluff, Arkansas, 1976

Formulation	Carbofuran rate	Seed quality[1]			Seed yields	
	10G/inch d.b.h.	Filled	Empty	Seedbug-damaged	Seeds/ cone	Filled seeds/cone
	Oz	----- Percent[2] -----			-- No.[2] --	
	0	77.8a	22.0a	0.2a	98a	76a
Liquid[3]	4	88.7a	11.2a	.1a	97a	86a
	8	91.8a	7.6a	.6a	103a	95a
	16	91.7a	8.2a	.1a	106a	97a
Granules	4	73.9a	25.5a	.6a	83a	61a
	8	72.6a	26.9a	.5a	97a	70a
	16	90.2a	9.5a	.3a	103a	93a

[1] By radiographic analysis.
[2] Any two means (within a column) followed by the same letter are not significantly different at the 5 percent level by Duncan's new multiple range test.
[3] Furadan® Flowable applied at rates equivalent to indicated dosages of Furadan® 10G.

Table 7.--Average seed quality and yield per cone for slash pine trees protected with carbofuran applied by three different methods at Leakesville, Mississippi

Year	Carbofuran rate	Application method	Seed quality[1]			Seed yields		
	10G/inch d.b.h.[2]		Filled	Empty	Seedbug-damaged	Seeds/ cone	Filled seeds/ cone	Increase in filled seeds/ cone[3]
	Oz		--- Percent[4] ---			-- No.[4] --		Percent
1974	0		76.5a	13.8a	9.7a	33a	25a	--
	8	Band	86.8b	9.8a	3.4b	63b	55b	120
	8	Drill	86.0b	11.1a	2.9b	49ab	42ab	--
	8	Broadcast	85.8b	11.1a	3.1b	57b	49b	96
	16	Broadcast	91.8b	5.9a	2.3b	65b	60b	140
1975	0		77.0a	19.4a	3.6a	80a	62a	--
	8	Band	83.3ab	15.3ab	1.4b	92ab	77ab	--
	8	Drill	90.8b	8.2b	1.0b	113b	103b	66
	8	Broadcast	90.3b	9.1b	.6b	105ab	95b	53
	16	Broadcast	89.4b	9.2b	1.4b	104ab	93b	50

[1] By radiographic analysis.
[2] Total amount/year; split applications 4/4/74, 6/6/74, and 4/7/75, 6/6/75.
[3] Calculated only when treatment mean differed significantly from check mean.
[4] For each year, any two means (within a column) followed by the same letter are not significantly different at the 5 percent level by Duncan's new multiple range test.

Table 8.--Survival of the 1975 cone crops on trees protected with carbofuran at three seed orchards

Orchard location and species	Treatment	Trees	Conelets tagged	Survival
		-- No. --		Percent $\bar{x}$ (range)
Cochran, Ga.				
Loblolly pine[1]	Check	9	386	81 (43-91)
	Carbofuran (5.3 oz/inch d.b.h., applied 4/4, 6/6, 7/23/74)	6	207	93 (90-100)
	Carbofuran (16 oz/inch d.b.h., applied 4/4/74)	6	218	99 (88-100)
Greensboro, Ga.				
Loblolly pine[2]	Check	11	582	76 (5-93)
	Phorate (16 oz/inch d.b.h., applied 3/28/74)	4	243	82 (67-98)
	Carbofuran (5.3 oz/inch d.b.h., applied 3/28, 5/28, 7/1/74)	4	170	82 (71-100)
	Carbofuran (16 oz/inch d.b.h., applied 3/28/74)	4	206	97 (93-100)
Rincon, Ga.				
Slash pine[3]	Check	10	132	16 (0-39)
	Carbofuran (16 oz/inch d.b.h, applied 3/21/74)	5	125	87 (75-100)

[1] Tagged 4/4/74; final tally 10/30/75.
[2] Tagged 3/28/74; final tally 10/6/75.
[3] Tagged 3/14/74; final tally 9/10/75.

Table 9.--Average seed quality and yield per cone for trees protected with carbofuran or phorate the previous year[1]

Orchard location, species, and insecticide	Insecticide rate		Seed quality[2]			Seed yields		
	10G/inch d.b.h.	Applications[3]	Filled	Empty	Seedbug-damaged	Seeds/cone	Filled seeds/cone	Increase in filled seeds/cone[4]
	Oz	No.	Percent[5]			No.[5]		Percent
Greensboro, Ga.								
Loblolly pine	0	0	86.6a[4]	11.5a	1.9a	83a	72a	--
Carbofuran	4	1	92.6a	6.3a	1.1a	107ab	99ab	--
	8	1	87.5a	10.6a	1.9a	122b	106b	47
	16	1	88.6a	11.0a	.4b	99ab	88ab	--
	4	3	89.7a	8.1a	2.2ab	109ab	98ab	--
	8	3	91.1a	8.2a	.7b	106ab	97ab	--
	16	3	91.5a	8.1a	.4b	120b	110b	53
Phorate	4	1	86.5a	10.8a	2.7a	108ab	93ab	--
	8	1	86.4a	13.4a	.2b	118ab	102ab	--
	16	1	90.3a	9.3a	.4b	114ab	103b	43
Woodbine, Ga.								
Slash pine	0	0	67.0ab	25.3ab	7.7a	80a	54a	--
Carbofuran	4	1	72.0abc	23.8abc	4.2ab	99ab	71ab	--
	8	1	78.9bc	17.1bc	4.0ab	120bc	95bc	76
	16	1	85.2c	11.7c	3.1b	133c	113c	109
	4	2	61.9a	31.6a	6.5ab	87a	54a	--
	8	2	78.4bc	16.3bc	5.3ab	115bc	90bc	67
	16	2	81.0c	16.6bc	2.4b	119bc	96bc	78

[1] Applications made only in 1974; cones harvested in 1975.
[2] By radiographic analysis.
[3] Number of applications administered to obtain indicated dosage.
[4] Calculated only when treatment mean differed significantly from check mean.
[5] For each seed orchard, any two means (within a column) followed by the same letter are not significantly different at the 5 percent level by Duncan's new multiple range test.

Table 10.--Average seed quality and yield per cone for trees protected with two annual applications of carbofuran

Orchard location and species	Carbofuran rate	Seed quality[1]			Seed yields		
	10G/inch d.b.h.[2]	Filled	Empty	Seedbug-damaged	Seeds/cone	Filled seeds/cone	Increase in filled seeds/cone[3]
	Oz	Percent[4] $\bar{x}$ (range)			No.[4] $\bar{x}$ (range)		Percent
Lumberton, N. C.							
Loblolly pine	0	52.1a (13-72)	37.3a (20-63)	10.5a (1-27)	61a (33-123)	32a (7-56)	--
	4	86.3b (63-96)	12.5b (4-35)	1.2b (0-4)	115b (94-142)	99b (60-131)	209
	8	88.9b (73-98)	10.7b (2-26)	.4b (0-1)	127b (97-170)	113c (70-161)	253
New Kent, Va.							
Loblolly pine	0	80.2a (67-92)	18.0a (8-30)	1.8a (0-8)	65a (15-115)	52a (13-95)	--
	8	85.2b (66-94)	13.9b (6-33)	.9a (0-7)	100b (33-138)	85b (31-124)	63
	16	85.9b (75-93)	13.6b (6-24)	.6a (0-2)	99b (55-147)	85b (42-137)	63
Rincon, Ga.							
Slash pine	0	64.7a (19-99)	26.4a (0-77)	8.9a (1-19)	54a (17-110)	35a (3-80)	--
	4	85.8b (70-92)	10.8ab (5-18)	3.4b (0-13)	96b (86-107)	82b (62-92)	134
	8	97.8b (96-99)	1.0b (0-4)	1.1b (0-2)	99b (71-126)	97b (71-120)	177
	16	96.5b (91-100)	3.1b (0-8)	.4b (0-1)	104b (74-151)	100b (68-151)	186
	Guthion[5]	78.3 (37-99)	17.0 (0-57)	4.7 (0-17)	77 (34-151)	60 (17-97)	71

[1] By radiographic analysis.

[2] One application/year (4/15/74, 2/12/75 at Lumberton; 4/1/74, 2/20/75 at New Kent; 3/21/74, 2/14/75 at Rincon).

[3] Calculated only when treatment mean differed significantly from check mean.

[4] For each orchard, any two means (within a column) followed by the same letter are not significantly different at the 5 percent level by Duncan's new multiple range test.

[5] Operational azinphosmethyl (Guthion®) spray schedule.

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1973. Southwide tests of carbofuran for seedbug control in pine seed orchards. U.S. Dep. Agric. For. Serv., Res. Pap. SE-105, 24 p. Southeast. For. Exp. Stn., Asheville, N. C.

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Keywords: Phorate, Leptoglossus corculus, Tetyra bipunctata, Pinus taeda, P. elliottii var. elliottii, P. echinata, P. virginiana.

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Relation of Oak Abundance, Seed Source, and Temperature to Geographic Patterns of Fusiform Rust Incidence

by
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Ronald J. Dinus
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and
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Southeastern Forest Experiment Station

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Southeastern Forest Experiment Station
Asheville, North Carolina

Relation of Oak Abundance, Seed Source, and Temperature to Geographic Patterns of Fusiform Rust Incidence

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Abstract.--Rust incidence in slash pine plantations was strongly correlated with abundance of water oak (r = 0.68) and moderately or weakly correlated with abundance of six other oak species (r = 0.23 to 0.48). Incidence in loblolly pine was positively correlated only with water (r = 0.42) and laurel oak (r = 0.48) volumes. The lower correlation coefficients in loblolly may result from planting of rust-resistant stock in some regions. With oak volume held constant, incidence tended to be greatest in areas where April-May temperatures ranged from about 67° to 70° F; plantations in warmer or cooler regions had less infection. When water and laurel oak volumes were considered along with April-May temperatures, multiple correlations with incidence were 0.77 for slash pine and 0.55 for loblolly pine. Although geographic origin of seed can greatly affect the amount of rust in plantations, it did not appear to be a major cause of the regional patterns of incidence. Further study is needed, but these findings suggest that forest managers should consider oak abundance (especially water oak) and average spring temperatures in assessing rust hazard.

Keywords: Cronartium fusiforme, loblolly pine, Pinus taeda, slash pine, P. elliottii, Quercus, forest tree diseases, epidemiology.

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[1] Formerly with the Southern Forest Experiment Station, Gulfport, Mississippi.

Fusiform rust (Cronartium fusiforme Hedgc. & Hunt ex. Cumm.) has reached epidemic proportions in many areas of the Southern United States (Griggs and Schmidt 1977) and poses a continuing threat to efficient management of loblolly (Pinus taeda L.) and slash (P. elliottii Engelm.) pines (Dinus 1974). Economic consequences are severe, with losses conservatively estimated at $28 million annually (Powers and others 1974).

Although disease incidence is widespread and localized areas of high incidence occur sporadically, rust is most prevalent in a corridor extending from southeastern Louisiana through southern and central Mississippi, Alabama, Georgia, and South Carolina (Phelps 1973; Powers and others 1974; Schmidt and others 1974; Squillace 1976). Furthermore, incidence in the corridor decreases gradually to the northwest and southeast (figs. 1 and 2).

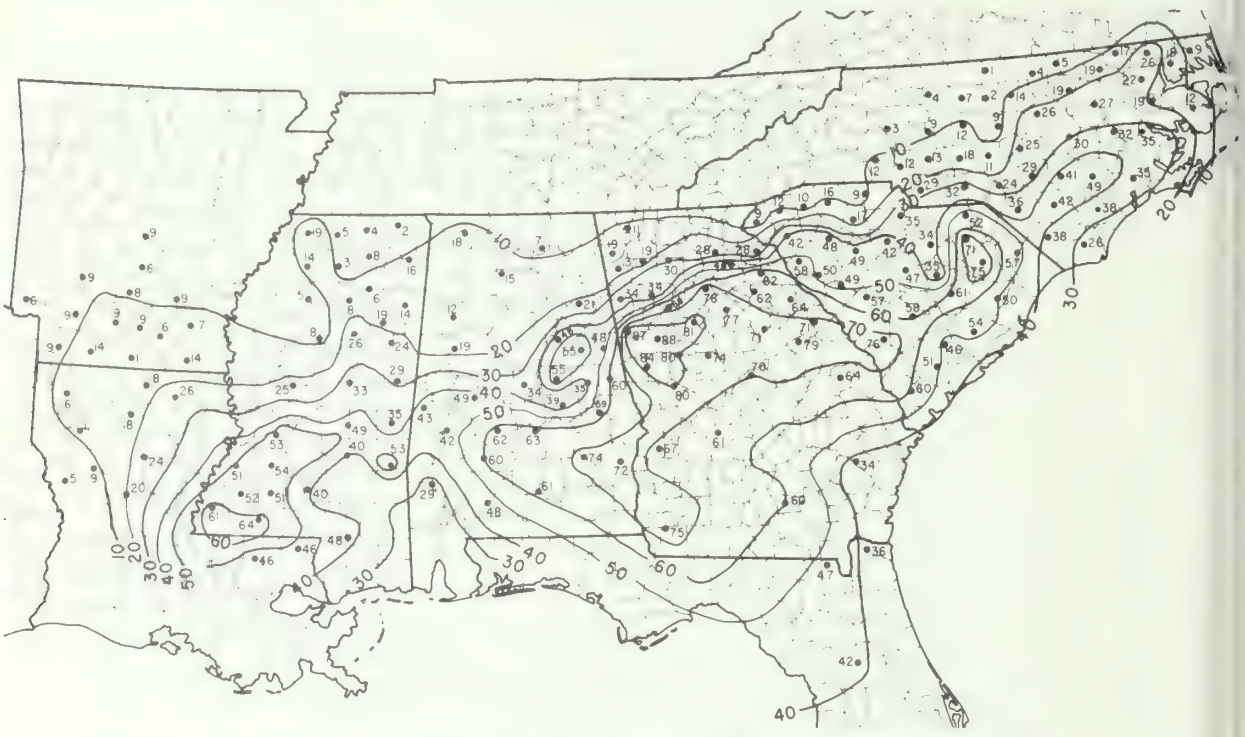

Figure 1.--Percentages of trees infected with fusiform rust in 8- to 12-year-old loblolly pine plantations. (From Squillace 1976, based largely on data from Phelps 1973.)

In the rust corridor, Dinus (1974) suggested that incidence varies in proportion to the intensity of forest management and is greatest where pine and oak distributions maximally coincide. In a study in northern Florida, Hollis and Schmidt (1977) showed that frequency of oak hosts, amount of susceptible pine shoot tissue, amounts of extractable soil phosphorus, and degree of internal soil drainage strongly influenced disease incidence. Climate was uniform and did not limit rust development. Oak abundance was the single most important factor and rust was most prevalent where susceptible pines and oaks grew best and in association with one another.

The relative importance of site factors remains uncertain, especially on a regional scale. Following Weltzien's (1972) suggestions for study of plant diseases in general, we herein examine probable causes of fusiform rust distribution on a regionwide basis. Emphasis is placed on geographic origin of

seed, oak abundance, and climate. We hope our report will expedite the development of rust-hazard rating systems and regional strategies for managing fusiform rust.

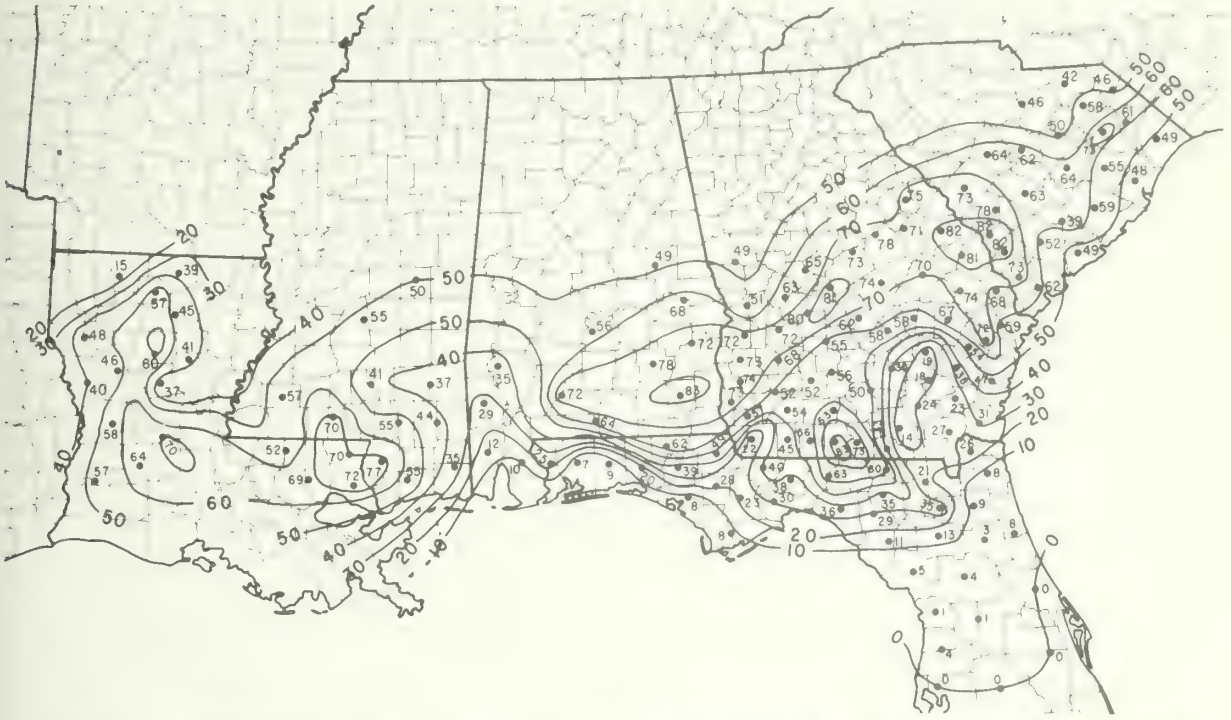

Figure 2.--Percentages of trees infected with fusiform rust in 8- to 12-year-old slash pine plantations. (From Squillace 1976, based on data from Phelps 1973.)

MATERIALS AND METHODS

FUSIFORM RUST INCIDENCE DATA

In a recent survey 1,319 loblolly and 1,173 slash pine plantations were examined for rust incidence (Phelps 1973). Plantations were 8 to 12 years old, of unknown seed origin, and scattered across much of the species ranges. Percentages of trees with stem and/or branch galls were analyzed. To facilitate analyses, survey data were averaged by county when there were five or more plantations in the county. Rust data from adjacent counties having less than five plantations surveyed were combined, resulting in 187 sampling areas for loblolly pine and 156 for slash pine.

OAK ABUNDANCE DATA

Data on oak abundance were obtained from standard survey plots of the U.S. Forest Service. For each of seven oak species, the average cubic-foot volume per acre in stems 1 inch d.b.h. and larger on commercial forest land was obtained. County averages were combined as necessary to conform to the sampling areas for the rust incidence data.

Multiple-regression analyses were used to study relationships between incidence of rust, prevalence of oaks, and climatic factors.

PINE SEED-SOURCE DATA

Since the plantations surveyed for incidence were of unknown seed origin, we utilized published seed-source data to investigate possible effects of seed origin on rust incidence patterns. The seed-source study plantations varied in age at last observation (5 to 12 years) and date of planting, so adjustments were made for effects of these factors. Percentages of infected trees, as reported

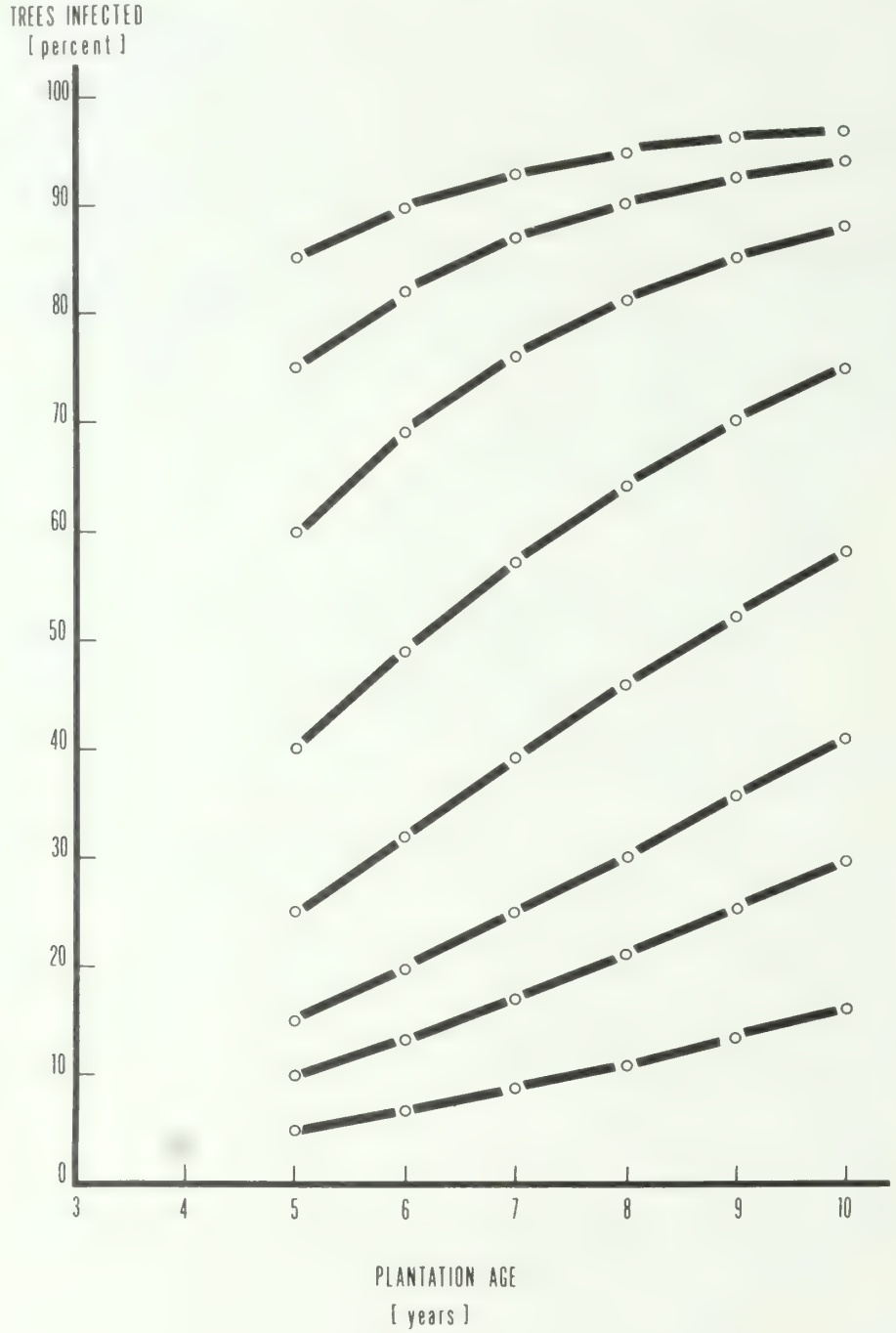

Figure 3.--Chart for adjusting observed percentage of trees infected with fusiform rust in loblolly and slash pine in seed-source study plantations less than 10 years old. (From Schmidt and others, 1977.)

by various authors, were extrapolated to age 10 using figure 3, adapted from Schmidt and others (1977). As an example, if a seed source in a plantation measured at 7 years of age had 50 percent infection, we estimated that infection would be 68 percent at 10 years of age.

Schmidt and others (1974) showed that recent slash pine plantations had more infection at a given age than those established earlier. Rates of increase averaged about 3 percent per year, and their equation was used to construct a regression of infection at 10 years over planting date (solid line in figure 4). The line applies strictly to the average rates of infection in their study. For example, plantings made in 1950 having a 10th-year infection of 16 percent would be expected to have about 40 percent infection if planting had been delayed until 1960. To facilitate estimates for plantings having greater or lower rates of infection than shown on the regression line, the dashed lines were drawn in figure 4. They were drawn through proportionate points above and below the regression line. For example, the first dashed line below the regression line is drawn through points at one-fourth the distance between the regression and the "0" axis. All available seed-source data were then adjusted to a 1962 planting date, using figure 4. As an example, if a seed source planted in 1956 had 40 percent infection at age 10 years, we estimated that if it had been planted in 1962 instead, it would have about 55 percent infection at age 10. (Although this adjustment technique was based on slash pine data, we assumed it would also be applicable to loblolly pine.)

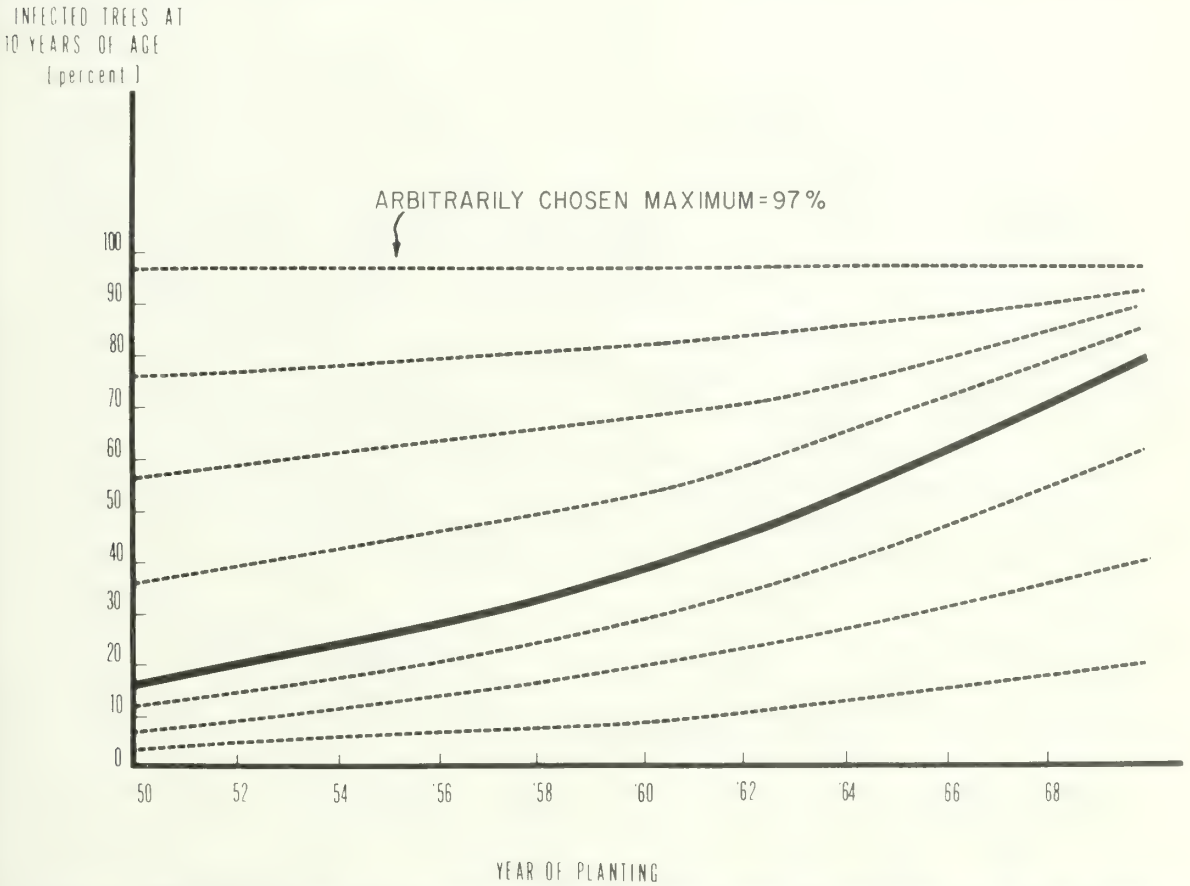

Figure 4.--Chart for adjusting observed percentage of trees infected with fusiform rust in loblolly and slash pine plantations, for effect of planting date. (Solid line is based on equation in Schmidt and others 1974.)

RESULTS AND DISCUSSION

RELATION OF RUST INCIDENCE TO PINE SEED ORIGIN

Considerable variation in rust susceptibility occurs among pines from different parts of the species ranges (Wells and Wakeley 1966; Gansel and others 1971). Such variation is especially high in loblolly pine, in which seed x planting site interaction is low. To determine if seed origin had appreciable effects on the incidence patterns developed from the 1971-73 survey, we first compared performance of local trees in each of the many seed-source plantations (figs. 5 and 6) to that of the 1971-73 survey (figs. 1 and 2). The patterns are not greatly different, especially in loblolly pine for which much data were available. As in the 1971-73 survey data, infection in local sources increases from southeast to northwest, reaching a high in the corridor and decreasing beyond it. Average infection for nonlocal seed sources in each plantation was also examined and the pattern was again similar. Strong correlations were found between performance of the local source and the average of all nonlocal sources, in both species (r = 0.95 for loblolly and 0.99 for slash pine). The

Figure 5.--Percentages of native loblolly pines infected with fusiform rust in seed-source tests, adjusted to age 10 years and 1962 planting date. (Data from Wells and Wakeley 1966; Kraus 1967; Crow and Hansbrough 1970; Cole 1972; Goggans and others 1972; Grigsby 1973, 1975; and Draper 1975.)

Figure 6.--Percentages of native slash pines infected with fusiform rust in seed-source tests, adjusted to age 10 years and 1962 planting date. (Data from Gansel and others 1971; Cole 1972; a 1971 Office Report from Southeastern Forest Experiment Station 1971; and personal communications from R. E. Goddard and O. O. Wells.)

similarity of infection patterns for both local and nonlocal seed sources to those developed from the 1971-73 survey suggests that seed-origin effects on geographic patterns of incidence were minimal.

Statistical analyses of data from the Southwide Pine Seed Source Study (tables 1 and 2) support the above findings. Seed-source effects were appreciable (accounting for an average of 14 percent of total variance), but plantation effects were considerably greater (accounting for about 73 percent of the total variance).

In spite of the indications that the major factors responsible for the incidence patterns are mainly those of site, in some instances variations may be due to seed origin. For example, slash pine plantations in central Louisiana had much infection (fig. 2), while loblolly pine plantations there contained considerably less infection (fig. 1). Perhaps seed from resistant sources was used in the loblolly plantings. But the results as a whole suggest that the general patterns of infection observed in the 1971-73 survey are due mainly to site factors. Presumably, if relatively resistant seed is planted over the whole region, the level of infection would be low but the overall pattern of variation in infection would be similar to that obtained from the 1971-73 survey.

Table 1.--Percentages of loblolly pines from various origins infected with fusiform rust when planted at various localities, at 10 years of age. (Compiled from Wells and Wakeley, 1966, Series 1 data.)

Planting site (county and state)	Seed origin (county and state)						
	Angelina, Tex.	Clark, Ark.	Somerset, Md.	Pamlico, N. C.	Jefferson, Ala.	Wilcox & Crisp, Ga.	Averages
	Percent						
Worchester, Md.	0	0	0	0	0	0	0
Cherokee, Tex.	0	0	0	0	0	0	0
Craven, N. C.	0	0	0	2	3	7	2
Clark, Ark.	0	1	1	9	4	17	5
Dooly, Ga.	5	6	13	48	41	52	27
Pearl River, Miss.	8	15	20	45	48	44	30
Talladega, Ala.	5	9	18	48	63	59	34
Washington, La.	25	47	45	82	91	83	62
Averages	5	10	12	29	31	33	20

ANALYSIS OF VARIANCE

Source	df	MS	F	Estimated components of variance (%)
Plantations	7	2,968	20.2**	62.7
Seed origins	5	1,211	8.2**	17.7
P x S	35	147	--	19.6
Total	47	--	--	--

** Significant at 0.01 level.

RELATION OF RUST INCIDENCE TO OAK ABUNDANCE AND DISTRIBUTION

Among the seven oak species for which volume data were available, water oak (Quercus nigra L.) distribution and abundance show the greatest correspondence with percentage of pines infected. Water oak volumes generally increase from south to north, reaching a maximum at the corridor of greatest rust infection and decreasing beyond it (fig. 7). Also, both water oak volume and percentage of infection are high in southwest Georgia and low in southeast Georgia and southern Alabama.

Volume of laurel oak (Q. laurifolia Michx.) (fig. 8) tends to be correlated with that of water oak, and hence also follows the pattern of infection on pines to some extent. However, high volumes of laurel oak extend into central and south Florida, where infection on slash pine is low. Maximum volumes for this species occur farther south than the region of greatest rust infection on loblolly pine.

Table 2.--Percentages of loblolly pines from various origins infected with fusiform rust when planted at various localities, at 10 years of age. (Compiled from Wells and Wakeley, 1966, Series 2 data.)

Planting site (county and state)	Seed origin (county and state)								
	Living-ston, La.	Harde-man, Tenn.	Onslow, N. C.	Pren-tiss, Miss.	Spauld-ing, Ga.	New-berry, S.C.	Clarke, Ga.	Clay, Ala.	Aver-ages
	Percent								
Craven, N. C.	4	5	7	5	7	9	11	5	7
Clark, Ark.	2	17	5	13	6	20	22	25	14
Newberry, S. C.	7	8	17	16	16	21	25	22	16
Pearl River, Miss.	22	39	38	48	53	58	65	57	47
Spaulding, Ga.	30	53	65	62	72	60	76	83	63
Winston, Miss.	19	62	66	79	95	79	82	78	70
Coosa, Ala.	48	67	82	89	90	95	87	97	82
Washington, La.	53	82	74	86	74	98	89	98	82
Averages	23	42	44	50	52	55	57	58	48

ANALYSIS OF VARIANCE

Source	df	MS	F	Estimated components of variance (%)
Plantations	7	7,862	100.8**	83.0
Seed origins	7	1,053	13.5**	10.4
P x S	49	78	--	6.6
Total	63	--	--	--

** Significant at 0.01 level.

The volume distributions of the remaining five species of oaks do not conform closely with infection patterns. Willow oak (Q. phellos L.) occurs over most of the pine region, but its volumes are relatively low, with the exception of some areas such as northeast Louisiana and east-central Arkansas. Volumes of northern red oak (Q. rubra L.) and black oak (Q. velutina Lam.) are high only in the extreme northern portions of the pine ranges. Volumes of post oak (Q. stellata Wangenh. var. stellata) and southern red oak (Q. falcata Michx. var. falcata) are high in northern and western portions of the pine ranges. Post oak is not a susceptible host but was included in the analyses because of its association with susceptible scrub oaks, for which data were not available.

Figure 7.--Volume of water oak on commercial forest lands (in cubic feet per acre).

Preliminary examination suggested that the relationship between rust incidence and oak volume was curvilinear. For example, the percentage of slash pines infected increased with volume of water oak up to about 80 cubic feet per acre and then leveled off (fig. 9). Because of this, curvilinear correlations were computed using the square of oak volumes along with unsquared volumes as independent variables.

The percentage of slash pines infected was positively and significantly correlated with the volume of all oak species (table 3). But, as expected, the correlation with water oak (0.68) was considerably larger than with other oaks. When water oak was used with other oaks in multiple regression analyses, the relationships with infection were no stronger than with water oak alone. Within the planted range of slash pine, water oak volumes were moderately correlated with volumes of other oaks; volumes of all species tended to increase from south to north. The correlations of these other oaks with pine infection were perhaps partly due to this association. When total volume of all oaks was used, the resulting correlation with infection (0.60) was less than that for water oak alone.

In an attempt to explain more of the variation in rust incidence, we weighted each species of oak according to Dwinell's (1974) ranking of susceptibility (table 4). The weights given in table 4 were multiplied by respective oak

Figure 8.--Volume of laurel oak on commercial forest lands (in cubic feet per acre).

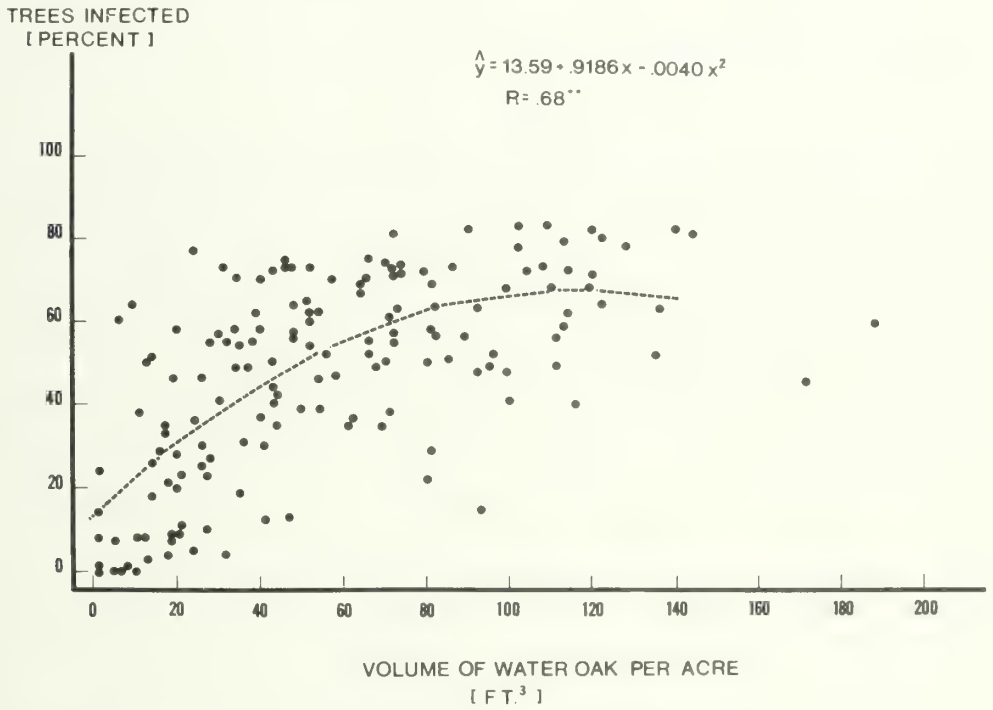

Figure 9. --Scatter diagram and curvilinear (quadratic) regression of percent infected slash pines and volume of water oak per acre on commercial forest lands.

Table 3.--Curvilinear correlations[1] between volume of oaks and percentage of trees infected with fusiform rust

Species	Loblolly pine	Slash pine
Water oak	0.42**	0.68**
Laurel oak	.48**	.26**
Willow oak	-.16*	.31**
Northern red oak	-.10	.23**
Black oak	-.30**	.29**
Post oak	-.38**	.48**
Southern red oak	-.32**	.43**
Water and laurel oaks	.54**	.69**
Unweighted total oak	.07	.60**
Weighted total oak[2]	.23**	.62**

[1] The square of oak volume is used with oak volume as an independent variable. Plus values indicate a general positive slope; negative ones indicate a general negative slope.

[2] See table 4 for assignment of weights.

* Significant at 0.05 level.

** Significant at 0.01 level.

Table 4.--Relative susceptibility of seven oak species (Dwinell 1974) and weights assigned for computing weighted total oak volumes

Species	Average number of telia/cm^2 of leaf surface	Weight, relative to water oak
Water oak	44.8	1.000
Willow oak	40.0	.893
Southern red oak	14.5	.324
Northern red oak	12.0	.268
Laurel oak	7.2	.161
Black oak	1.5	.033
Post oak	.4	.009

volumes in each plot and summed. Correlations were computed with these weighted sums as independent variables and with rust incidence as the dependent variable. The resulting correlation, 0.62 for slash pine, was only slightly greater than that for unweighted volumes.

Thus, intensity of infection in slash pine plantations is more strongly associated with geographic variation in the abundance of water oak than with that of any of the other oaks tested. Our findings agree with those of Hollis and Schmidt (1977), who found a correlation of 0.87 between water oak volume and infection in north Florida and also with Dwinell's (1974) ranking of water oak as the most susceptible to infection in response to artificial inoculation.

Relationships of infection in loblolly pine plantations to oak volumes were not as clear. Positive correlations were found for water oak (0.42) and laurel oak (0.48), while most correlations for the remaining oaks were significant but negative (table 3). When water oak and laurel oak were combined in a multiple correlation analysis, the correlation with rust infection in loblolly pine was 0.54, moderately higher than with either oak alone. All oaks combined showed little correlation with incidence, as expected, because some were individually negatively correlated. Weighting the oaks resulted in a highly significant but still rather low correlation (0.23).

The relatively low correlation of incidence with water oak volumes for loblolly pine, compared to those found for slash pine, may be due to natural resistance of loblolly pine in some parts of its range and the use of local seed in such cases. The resistance in some areas may be due to introgression with shortleaf pine (P. echinata Mill.), as pointed out by several authors. Some resistant sources are in areas where the abundance of water oak is high, which suggests that natural selection for resistance has also occurred. Use of local seed in such areas would also tend to weaken the correlation of rust incidence with water oak abundance.

Oaks other than those included in our analyses may be associated with intensity of pine infection. For example, blackjack (Q. marilandica Muenchh.), cherrybark (Q. falcata var. pagodaefolia Ell.), bluejack (Q. incana Bartr.), running (Q. pumila Walt.) and turkey (Q. laevis Walt.) oaks are moderately to highly susceptible (Dwinell 1974). Blackjack and cherrybark oaks could be important because they occur throughout the pine region. Turkey oak occurs over much of the Coastal Plains and could be important in those areas. Bluejack and running oaks also occur in the Coastal Plains but may not be important because of their limited leaf-surface area. The true role of such species is not certain and further research is necessary.

RELATION OF RUST INCIDENCE TO TEMPERATURE

Although prevalence of oaks was associated with variation in rust incidence, a large part of the variation remains unexplained. To examine the nature of the unexplained variation, we plotted the deviations from regressions of water and laurel oak volumes on rust incidence on maps. Generally, our regressions tended to underestimate infection in the corridor of high incidence and overestimate incidence in southern and northern areas. Such patterns suggest involvement of a factor or factors associated with latitude--possibly some aspect of climate. For example, low and high temperatures could limit fusi-

form rust in the North and South, respectively, while favorable temperatures for rust might occur in the corridor of high rust incidence. Therefore, temperatures during the pine infection period of April-May were analyzed. Mean temperatures (25- to 30-year analyses for April and May) (U.S. Weather Bureau 1959) alone and together with water and laurel oak volumes were used in regression analyses, with rust incidence being the dependent variable.

Results showed that mean April-May temperature was positively correlated with rust incidence in loblolly (R = 0.36) and negatively correlated with rust incidence in slash pine (R = -0.67). When temperature was used in combination with water and laurel oak volumes, R for loblolly pine increased only from 0.54 to 0.55, but for slash pine R increased from 0.69 to 0.77.

Incidence in loblolly pine was lowest in cooler areas (61°), increased with increasing temperatures to about 68°, and then decreased--the overall regression being positive (fig. 10). In slash pine, infection increased with increasing temperatures to 68° and then decreased rapidly, the overall regression being generally negative (fig. 11). Hence, the species fit an overall pattern, with infection relatively low in cool areas, maximum in areas with April-May temperatures of 68° to 69°, and low in areas with greater temperatures. In all areas, however, estimated infection increased curvilinearly with volume of water + laurel oak.

These data are in general agreement with data from north Florida where rust incidence increased directly with latitude and longitude (Schmidt and others 1974) and indirectly with temperatures, especially those during April and May (Schmidt 1973). Within this same area in north Florida, temperature and moisture conditions were favorable for pine infection by C. fusiforme much of the time (25 ± 3 days) during April and May (Hollis and Schmidt 1977).

Though accounting for significant proportions of the variation in incidence, regressions involving water oak, laurel oak, and mean April-May temperatures tended to over- or underestimate the severity of rust in certain portions of the region. The deviations from regression (figs. 12 and 13) should provide leads for further research. In loblolly pine, infection was overestimated along fringes of the species range and underestimated in southwest Mississippi and north-central Georgia (fig. 12). Overestimates, particularly west of the Mississippi River, may be associated with the greater resistance of loblolly native to that area (Wells and Wakeley 1966) or reduced moisture availability (Walterscheidt and Van Arsdel 1975). Underestimates, on the other hand, occurred where native pines are susceptible, oaks are abundant, temperatures are suitable, and where much planting has occurred in conjunction with intensified forest management. Increased availability of succulent, susceptible pine host tissue may be implicated in such areas, as a result of either increased planting (Dinus 1974) or faster growth (Hollis and Schmidt 1977).

For slash pine, our regressions overestimated incidence of rust in central Mississippi and southwest Alabama (fig. 13)--areas with limited planting in recent years. Underestimates for slash pine occurred in central Louisiana, southwest Mississippi, southeast Alabama, and southwest and central Georgia.

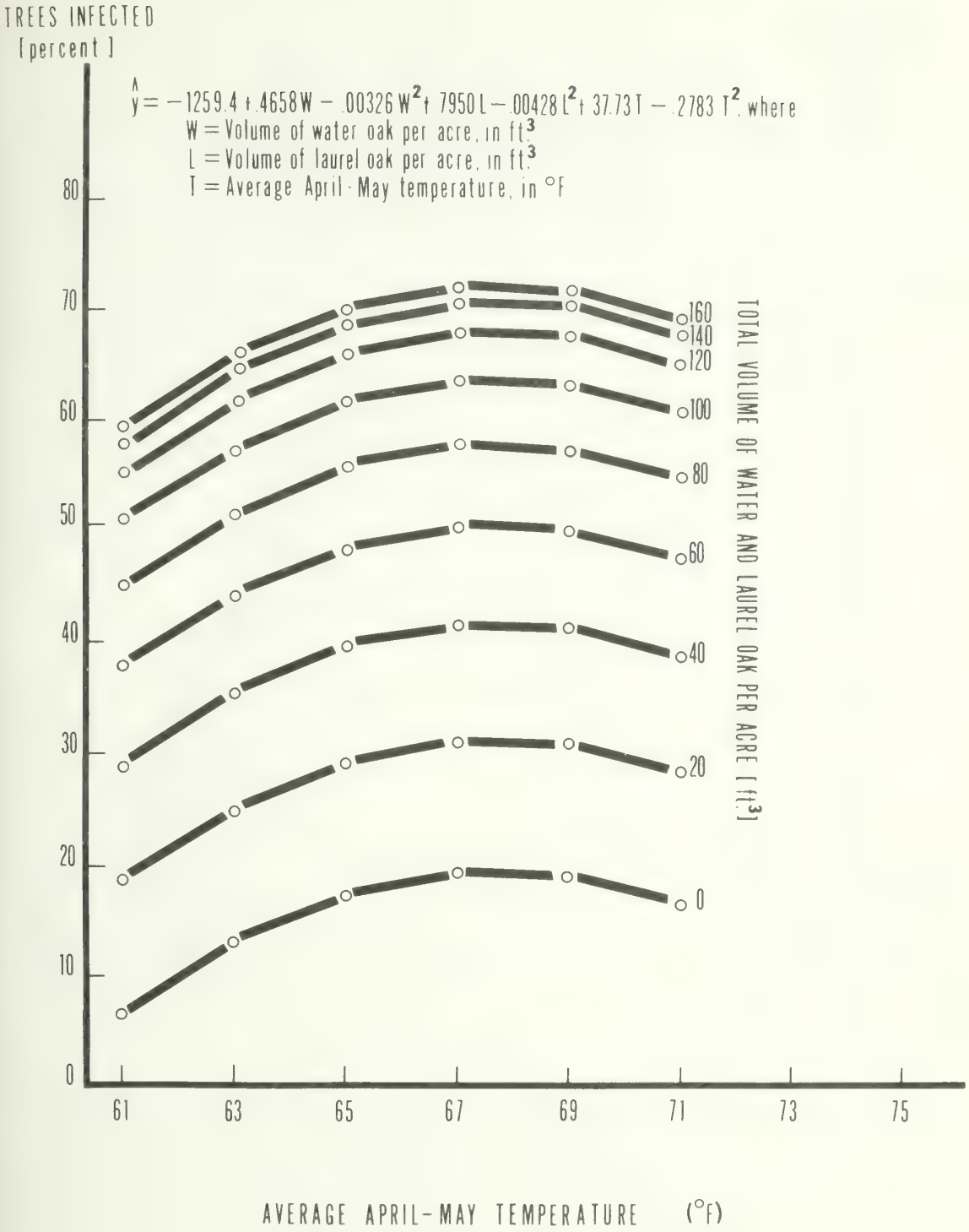

Figure 10.--Percentages of trees infected with fusiform rust in 8- to 12-year-old loblolly pine plantations, estimated from volumes of water and laurel oak, and average April-May temperature.

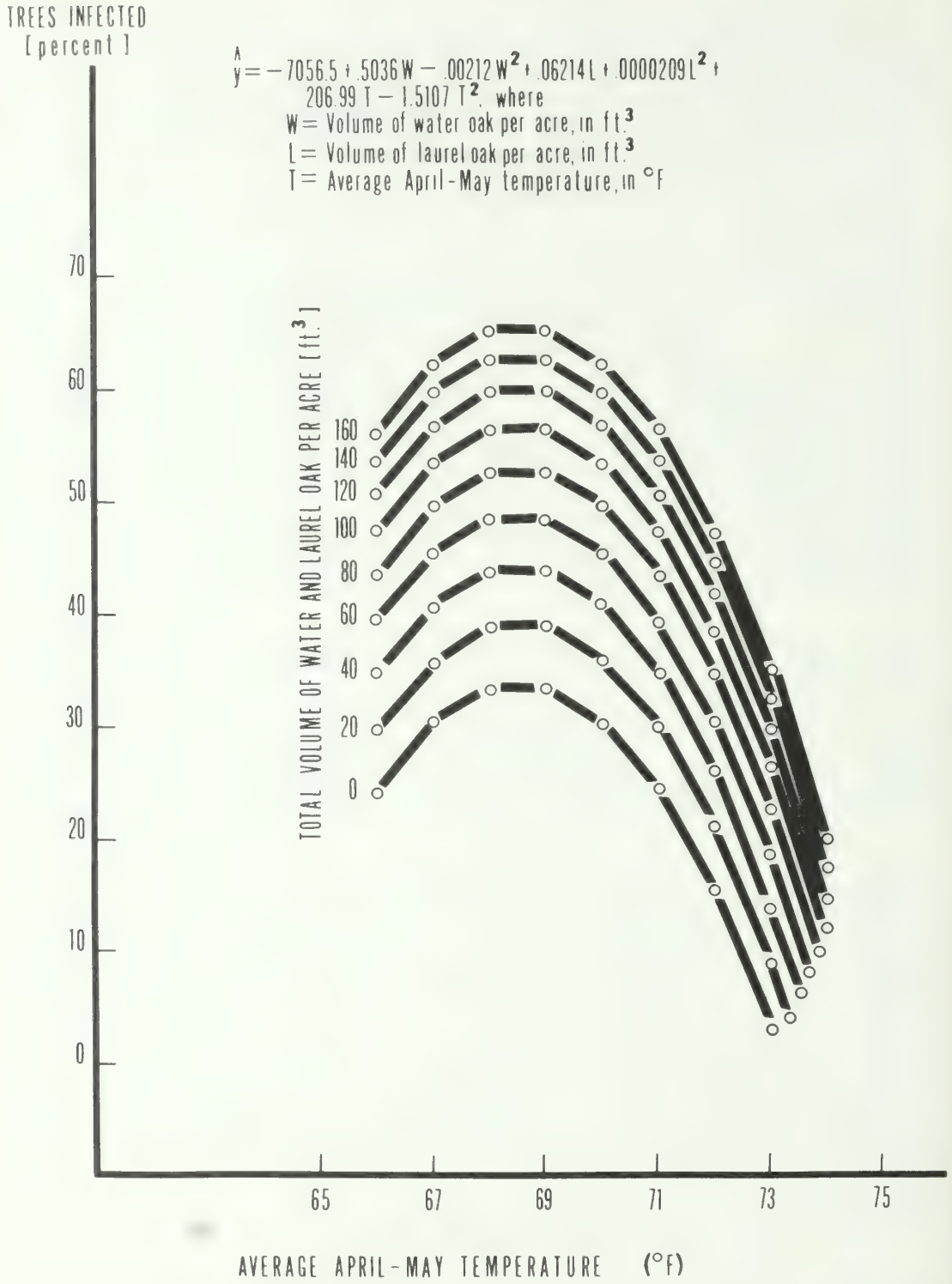

Figure 11.--Percentages of trees infected with fusiform rust in 8- to 12-year-old slash pine plantations, estimated from volumes of water and laurel oak, and average April-May temperature.

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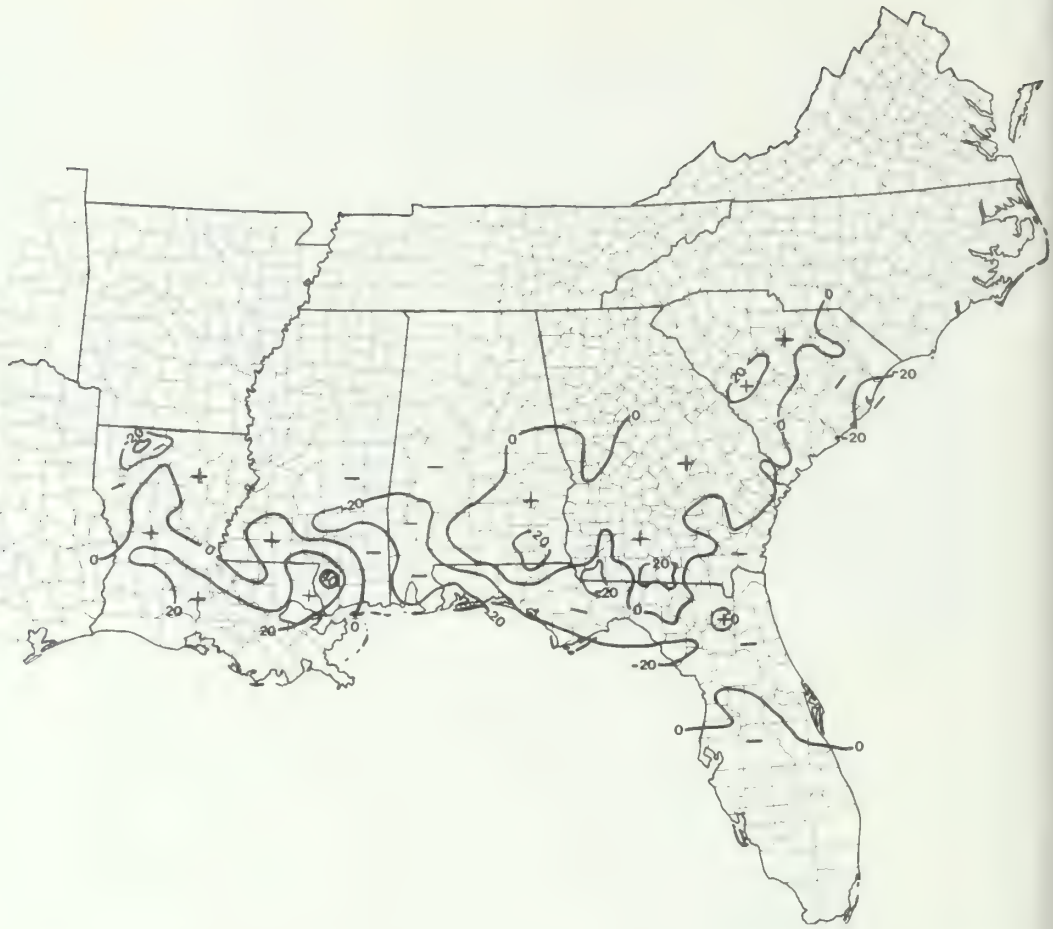

Figure 13.--Deviations from regression of percentage of slash pines infected on volumes of water oak and laurel oak on average April-May temperature. Plus values indicate levels of infection greater than expected from regression (underestimates), while minus values indicate levels of infection less than expected from regression (overestimates).

CONCLUSIONS

The most significant regionwide factor associated with rust incidence was abundance of oaks. In slash pine, incidence was strongly related to abundance of water oak and weakly or moderately associated with other oaks. In loblolly pine, incidence was positively, but not strongly, correlated with abundance of only water and laurel oak. The relatively weak relationship of oak abundance for loblolly pine may be caused by natural resistance in some regions. Such resistance may have developed through natural selection in regions where water oak is abundant or through hybridization with shortleaf pine. Other oaks, not studied, may also be involved where they are prevalent and coincide with pine plantings.

Some variation in the pattern of rust incidence is independent of oak volume. This is especially true for slash pine in areas having mean April-May

temperatures ranging from 67° to 70° F; plantations in warmer or cooler regions had considerably less infection. The same pattern occurred for loblolly pine, but location effects were not as strong. The decrease in infection toward colder regions may have been due to unfavorable temperatures for inoculation or to other climatic factors correlated with temperature. The same may be true for the decrease in infection toward warmer regions. Further study of the particular climatic factors involved is needed.

Thus, we conclude that the major factor associated with rust incidence in loblolly and especially slash pine is the abundance of water and perhaps laurel oaks. In addition, April-May temperatures or associated climatic factors were related to rust incidence. We suggest that forest managers consider oak abundance and average spring temperatures in assessing rust hazard. Rate of infection in existing pine plantations should also be considered, but it should be remembered that incidence has been increasing in many areas.

ACKNOWLEDGMENT

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Rust incidence in slash pine plantations was strongly correlated with abundance of water oak (r = 0.68) and moderately or weakly correlated with abundance of six other oak species (r = 0.23 to 0.48). Incidence in loblolly pine was positively correlated only with water (r = 0.42) and laurel oak (r = 0.48) volumes.

Keywords: Cronartium fusiforme, loblolly pine, Pinus taeda, slash pine, P. elliottii, Quercus, forest tree diseases, epidemiology.

Squillace, A. E., Ronald J. Dinus, Charles A. Hollis, and Robert A. Schmidt
1978. Relation of oak abundance, seed source, and temperature to geographic patterns of fusiform rust incidence. U.S. Dep. Agric. For. Serv., Res. Pap. SE-186, 20 p. Southeast. For. Exp. Stn., Asheville, N. C.

Rust incidence in slash pine plantations was strongly correlated with abundance of water oak (r = 0.68) and moderately or weakly correlated with abundance of six other oak species (r = 0.23 to 0.48). Incidence in loblolly pine was positively correlated only with water (r = 0.42) and laurel oak (r = 0.48) volumes.

Keywords: Cronartium fusiforme, loblolly pine, Pinus taeda, slash pine, P. elliottii, Quercus, forest tree diseases, epidemiology.

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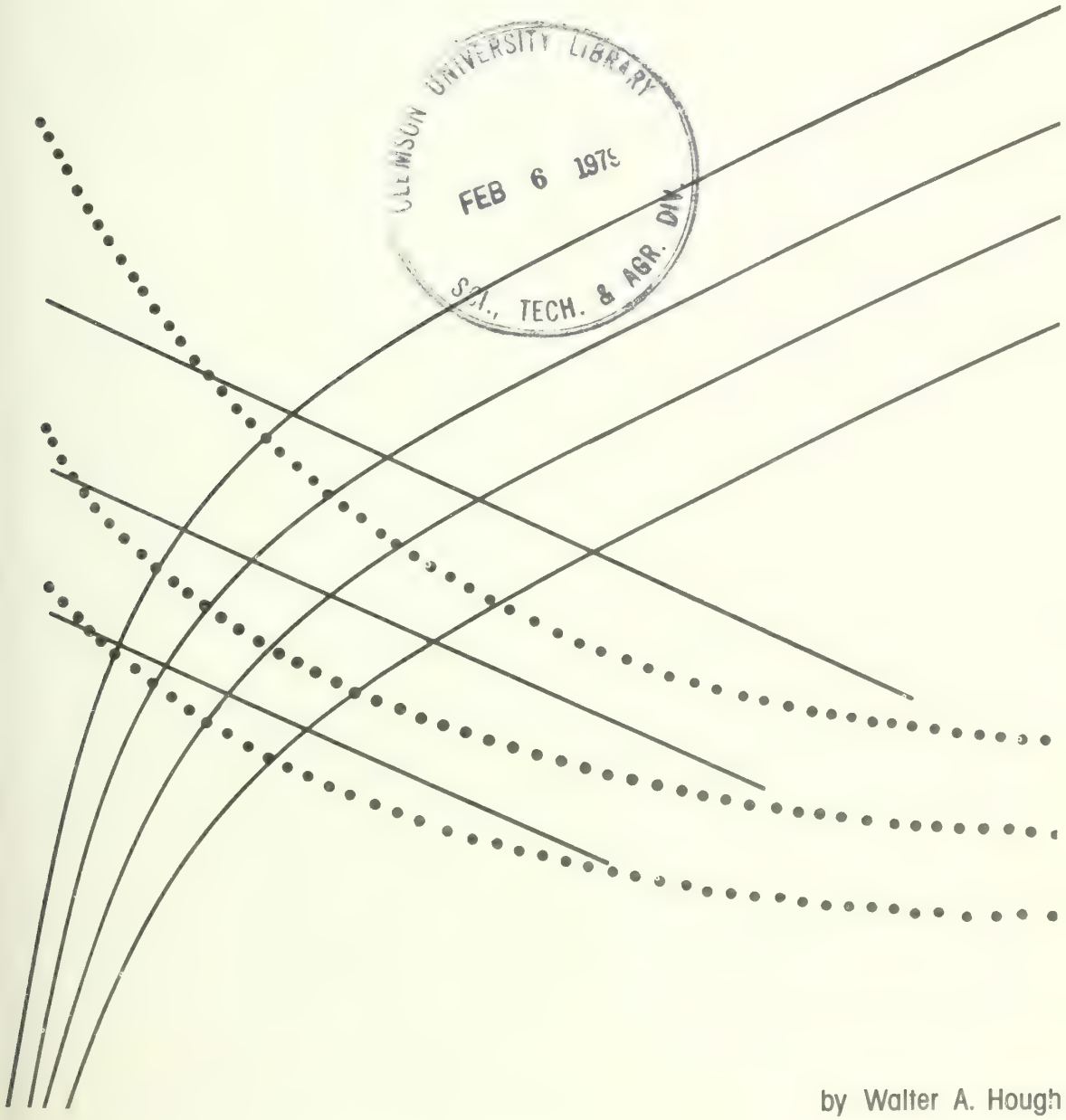
U.S. Department of Agriculture
Forest Service Research Paper SE-187

June 1978

Estimating Available Fuel Weight Consumed by Prescribed Fires in the South



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by Walter A. Hough

For the convenience of users, values in this Paper are reported in English units of measure, which are still most commonly used in southern forests. To convert these values to metric units, consult the table below.

To convert from	To	Multiply by
Acres	meter^2	4,047
Acres	hectares	0.405
Tons per acre	kilograms/meter^2	0.224
Tons per acre	metric tons/hectare	2.242
Pounds per ton	grams/kilogram	0.500
Pounds per ton	grams/metric ton	500
Inches	centimeters	2.540
Feet	meters	0.305
Square feet per acre	centimeters^2/meter^2	0.230

Southeastern Forest Experiment Station
Asheville, North Carolina

Estimating Available Fuel Weight Consumed by Prescribed Fires in the South

by

Walter A. Hough, Staff Fire Scientist
Forest Fire and Atmospheric Sciences Research
Forest Service, U.S. Department of Agriculture
Washington, D. C.[1]

Abstract.--A method is proposed for estimating the weight of fuel burned (available fuel) by prescribed fires in southern pine stands. Weights of available fuel in litter alone and in litter plus understory materials can be estimated. Prediction equations were developed by regression analysis of data from a variety of locations and stand conditions. They are most reliable for slash pine fuel types but should also provide close approximations for longleaf and loblolly pine types.

Information needed to make estimates includes: stand basal area, time since last disturbance (age of rough), and understory height. With these data, total litter layer dry weight and total understory dry weight can be estimated. Total litter layer moisture content is also needed and can be estimated by a procedure described here. Estimates of available fuel have standard errors of about ± 1.0 ton per acre. However, the accuracy of the method depends on the accuracy of input data. Points of weakness and possible misuse of tables are discussed.

Keywords: Prescribed burning, smoke management.

Forest managers need to predict the weight of fuel consumed by prescribed fires for a number of reasons. This value, called available fuel, is an indicator of fire intensity and the likelihood of the burn meeting the planned objectives, especially for fuel reduction. Available fuel is also needed to estimate smoke production and movement.

Previous work has been done on estimating available fuel in southern pine types (Hough 1968; Sackett 1975), but results are for limited situations and do not cover the needs of the southern forest smoke manager. In earlier work Hough (1968) found significant relationships among fuel consumption, initial fuel weight, and moisture content.

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[1] Formerly located at Southeastern Forest Experiment Station, Southern Forest Fire Laboratory, Macon, Ga.

I report here the results of multiple regression analyses. These results are combined with appropriate assumptions to produce equations for estimating available fuel weight for prescribed burns. The estimating equations were developed initially for the palmetto-gallberry-slash pine fuel type. However, a wider data base was used to permit appropriate predictions to be made in longleaf pine and loblolly pine types. Equations were selected for ease of application to currently available data as well as for accuracy.

EQUATION DEVELOPMENT

AVAILABLE LITTER LAYER WEIGHT

On 1960 and 1961 burns in slash pine stands, a number of variables were statistically related to, and useful for prediction of, amount of available fuel in the various fractions in the litter layer.[2] These fractions consist of the L or litter layer made up of freshly fallen foliage, the F or fermentation layer composed of weathered material whose origin can still be determined, and the H or humus layer made up of well-decomposed organic material.

The weight of available fuel in the combined L&F layers was highly correlated with the initial weight and moisture content of the L&F layers. Available weight in the H layer was significantly related to the initial weight of the H layer and to the amount of fuel burned in the combined L&F layer. Total litter layer weight reduction (L&F&H) correlated best with the initial weight of the total layer and the moisture content of the total layer (total wet-weight/total dry-weight calculations). These relationships were based on measurements from 28 test fires.

A method was needed to estimate litter consumption in a wide variety of prescribed burning situations throughout the South. Therefore, all available measurements that included dry weight and moisture content of the total litter layer before a burn, and fuel dry weight immediately after a burn, were obtained from the files at the Southern Forest Fire Laboratory. All data were from experimental prescribed burns, including backfires and strip headfires of relatively low intensity. Tests were made to see if backfires and headfires differed significantly in total litter layer consumption. Differences were significant: headfires consumed more litter. This finding does not agree with those of others which indicate greater consumption by backfires (Beaufait 1965; Hough 1968). Because our results were confounded by very light fuel weights and low moisture contents on most plots that were headfired, it was not possible to say the difference was due to the type of fire. Therefore, we decided to combine all data so that results could be used for low-intensity headfires as well as for backfires.

Ninety-seven burns were used in the final regression analysis; the year, general location, type of fire, fuel type, and number of burns are given in table 1. The most reasonable fit of the data, one with an R^2 value of 0.78 and a standard error of 0.93 ton per acre, is:

---

[2]Data and sampling procedures used in the data collecting are on file at the Southern Forest Fire Laboratory, Macon, Georgia.

$$W_{AL} = 3.4958 + 0.3833 (W_{TL}) - 0.0237 (M_{TL}) - 5.6075 (1/W_{TL})$$

where

W_{AL} = available litter fuel dry weight (tons/acre)

W_{TL} = total litter layer dry weight (tons/acre)

M_{TL} = moisture content of total litter layer (percentage of dry weight).

Table 1.--General information about test burns used in developing estimating equations

Year	Location of burn	Type of fire	Type of fuel	Number of burns
1959	Waycross, Ga.	Backfire	Slash pine-palmetto-gallberry	12
Do.	do.	Headfire	do.	4
1960	do.	Backfire	do.	14
Do.	do.	Headfire	do.	4
1961	do.	Backfire	do.	14
1967	Bainbridge, Ga.	do.	Slash pine-no understory	4
Do.	Charleston, S. C.	Headfire	Longleaf & loblolly pine-titi-gallberry	6
1968	do.	do.	do.	2
Do.	Bainbridge, Ga.	do.	Slash pine-no understory	6
Do.	Lake City, Fla.	do.	Longleaf pine-palmetto-gallberry	2
1969	do.	do.	do.	2
Do.	Bullard, Ga.	Backfire	Slash pine-palmetto-gallberry	5
Do.	Charleston, S. C.	Headfire	Longleaf & loblolly pine-titi-gallberry	6
1974	Cochran, Ga.	Backfire	Slash pine-no understory	4
Do.	do.	do.	Loblolly pine-no understory	1
Do.	do.	Headfire	Slash pine-no understory	1
Do.	Patterson, Ga.	Backfire	Slash pine-palmetto-gallberry	5
Do.	Homerville, Ga.	do.	Slash pine-gallberry	2
Do.	Lake City, Fla.	do.	Longleaf pine-palmetto-gallberry	3

Figure 1 shows available litter fuel values for preburn total litter weights ranging from 1 to 16 tons per acre and total layer moisture contents ranging from 10 to 200 percent. Total layer moisture content is computed using total layer wet and dry weights. It is possible to consume considerable fuel when total layer moisture content is quite high because moisture gradients in forest

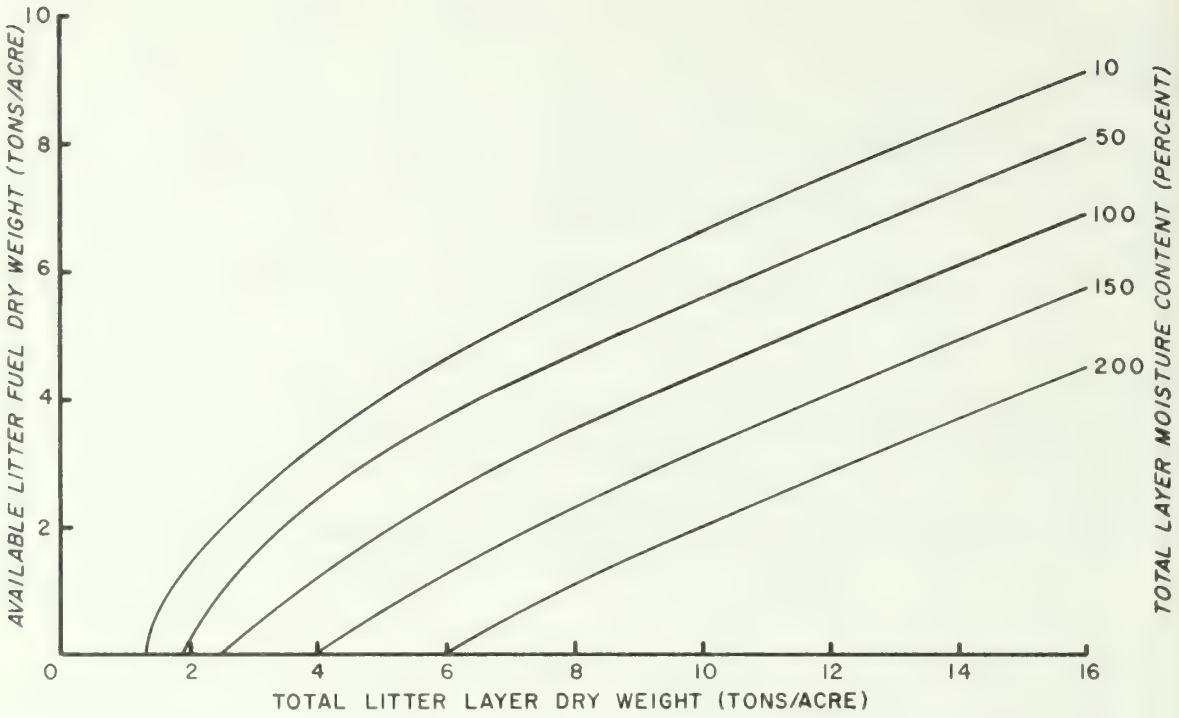

Figure 1.--Weight of total litter layer (L+F+H) consumed by prescribed fires.

floors with well-developed L, F, and H layers are steep. For example, at Waycross, Georgia, moisture content of the L layer was 17 percent, that of the F layer was 34 percent, and that of the H layer was 122 percent. The moisture content of the total layer was 79 percent, but the L and F layers were dry enough to burn while the H layer was too wet to burn. Plots at Cochran, Georgia, had even steeper gradients with the L layer being 20 percent, F layer 80 percent, and H layer 200 percent. The L layer would carry the fire, but that would be about all that would burn.

The nature of our basic data places several limitations on reliability of predictions. Only 2 of the 97 plots had preburn total litter weights above 15 tons per acre, and both of these had fairly high moisture contents. Thus, any litter reduction estimates for initial fuel weights above 15 tons per acre, especially at low total layer moisture contents, are questionable. On plots with a very light total layer (less than 2 tons per acre), moisture content did not exceed 30 percent; therefore, available fuel estimates at higher moisture contents may be in error. Experience has shown that 2 tons or less per acre of litter will not carry a backfire, nor probably a headfire, at moisture contents above 45 to 50 percent (fig. 1).

AVAILABLE LITTER AND AERIAL FUEL WEIGHT

It was necessary to develop a way to estimate available fuel in the understory as well as in the litter. Of the 97 plots used in the litter consumption analysis, 71 had aerial fuel-reduction measurements. Plots at Cochran, Bullard, and Bainbridge, Georgia (table 1) contained only surface fuels. Analyses of covariance indicated only small differences between backfires and headfires. These were again confounded by light understory fuel weights on headfire plots. Differences were not considered important enough to prevent pooling the data.

Multiple-regression analysis indicated possible ways to predict available aerial fuel weights. The first method required direct estimates of average moisture content of standing vegetation; the second did not. Since no convenient technique is available for estimating moisture content of standing vegetation, the second method was explored and adopted.

In the second method, the total litter layer's initial weight and moisture content and the initial weight of the standing fuel are used to estimate the total amount of available fuel. This approach provides the smoke manager with one consumption value that includes both litter and aerial fuel.

The most reasonable fit of the data, one with an R^2 of 0.86 and a standard error of ± 1.0 ton per acre, is:

$$W_{A(L+U)} = 3.2484 + 0.4322\ (W_{TL}) + 0.6765\ (W_{TU}) - 0.0276\ (M_{TL}) - 5.0796\ (1/W_{TL})$$

where

$W_{A(L+U)}$ = available litter plus understory fuel dry weight (tons/acre)

W_{TU} = total understory fuel dry weight (tons/acre).

Figure 2 shows total available fuel weights for preburn understory fuels weighing from 2 to 8 tons per acre and total litter layer weights of from 1 to 16 tons per acre for moisture contents of 10 and 200 percent. Some portions of the curves are extrapolated beyond observed data. For example, the heaviest plot had a standing fuel weight of 5.1 tons per acre; therefore, projections above approximately 5 tons per acre could be in error. Also, the plots with the lowest litter weights (2 tons per acre or less) had very low initial aerial fuel weights (1.1 tons per acre or less). Thus, the estimation of total available fuel for a combination of low litter weight, low litter moisture content, and high aerial fuel weight may be unreliable. Fortunately, very light litter layers with very heavy standing fuel weights seldom occur.

MOISTURE CONTENT OF TOTAL LITTER LAYER

Total litter layer moisture content must be estimated if available fuel is to be predicted. One simple approach would be to use the 100-hour timelag fuel moisture given in the National Fire-Danger Rating System (NFDRS) (Deeming and others 1972). The wetting of 100-hour fuel by precipitation as given in the NFDRS Manual is for stem and branch wood and does not account for the increase in total litter layer moisture content due to rainfall (Fosberg 1971). I therefore developed a new wetting curve reflecting total litter layer moisture contents of 200+ percent after 24 hours of rainfall.

Moisture retention capacity of total forest litter layers has been found to be between 200 and 300 percent of dry weight (Swank and others 1972; Metz 1958; Helvey 1964; Mader and Lull 1968; Van Wagner 1970). Thus, a litter layer weighing between 4 to 10 tons per acre can retain the equivalent of 0.2 inch of rainfall. After this amount has been taken up by the layers, additional rainfall has little effect on moisture content. Metz found that this maximum mois-

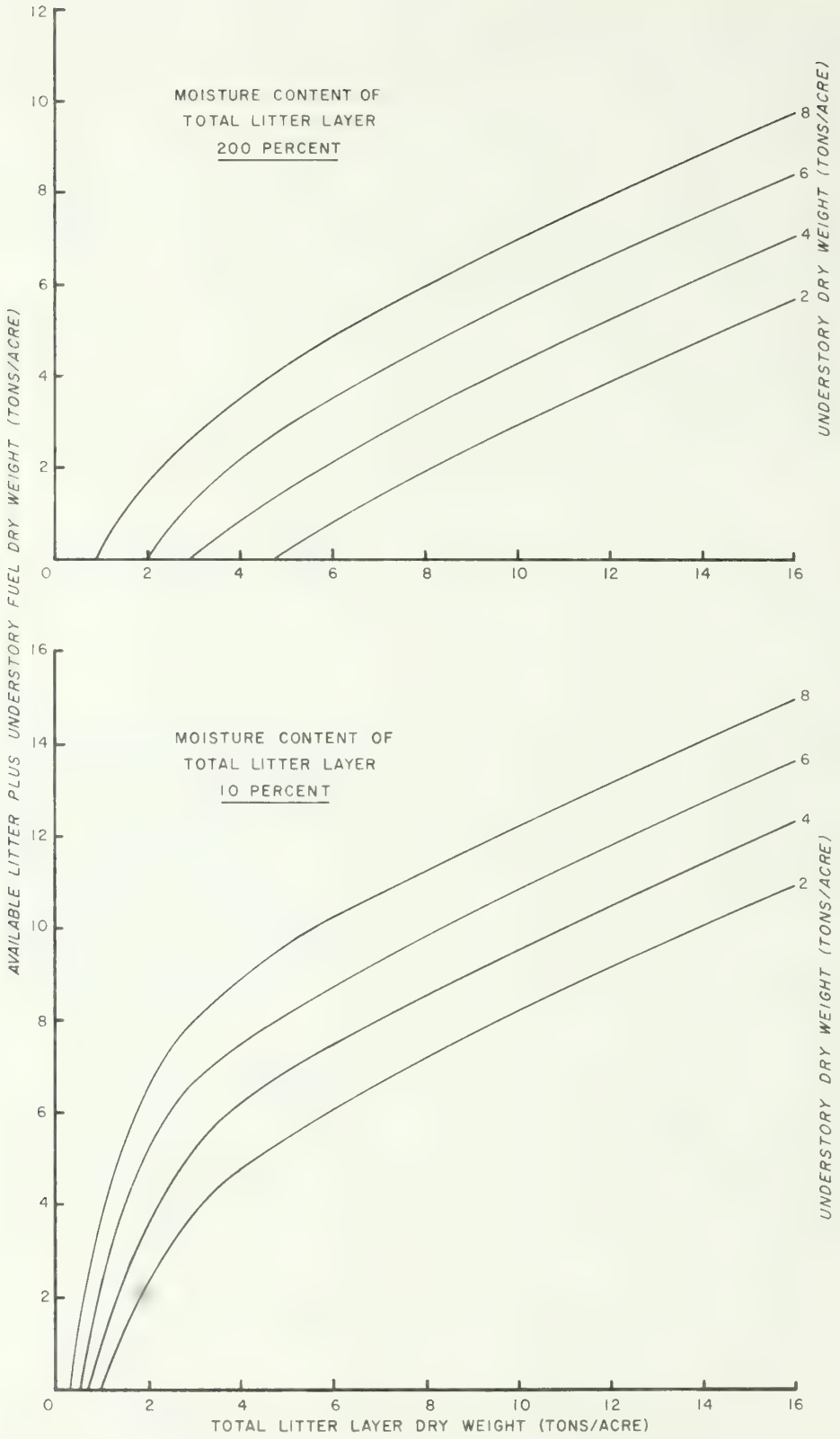

Figure 2. -- Available litter plus understory fuel weight varies with initial weight and moisture content of the total litter layer and initial weight of the understory.

ture content was reached only after prolonged rainfall periods--an indication that duration, as well as amount of rain, is important.

Duration effect was also shown by Paul,[3] who studied the effect of rate and amount of rainfall on pine litter moisture content. His data show that water uptake by pine litter begins to level off in 10 to 12 hours, regardless of amount of rainfall. The effect of rainfall on total layer moisture content is not clearly defined by his data. Also, I have found variations of 80 to 100 percent in total litter layer moisture content of square-foot samples collected over a brief period from a slash pine stand. Because the effects of rainfall rate are so unclear, only duration is considered here.

A single curve of total layer moisture content versus duration of precipitation was fitted to Paul's averaged data. I assumed that maximum total layer moisture content would not exceed 250 percent and that this value would be reached after 24 hours of rainfall. Figure 3 shows increases in total layer moisture content from rains of different durations. The equation for this curve is:

$$M_{TL} = 100.2261\ (RD^{0.3027}),$$

RD = rainfall duration (hours).

Fosberg (1975) has developed a theoretical model for predicting the moisture content of litter and duff (F&H layers). Since some of the physical properties of slash, longleaf, and loblolly pine litter layers required by that model are unknown, the model could not be tested.

Drying curves plotted from the NFDRS 100-hour timelag tables are similar to published curves for loblolly pine litter (Metz 1958) and eastern hardwood litter (Helvey 1964). However, the NFDRS curves approach 10 to 15 percent moisture content in about 7 days. These values are lower than total layer moisture contents measured in medium and heavy southern pine litter layers 7 days after a rain. In an effort to account for this difference, all data from experimental burn plots used in developing the available fuel predicting equations were analyzed to see if relative humidity, days since rain, and total weight of litter layer were correlated with total layer moisture content.

Multiple-regression analysis showed that days since rain (DSR) and total litter layer dry weight (W_{TL}) were significantly correlated with total layer moisture content (M_{TL}). Relative humidity was not significantly related to M_{TL} because humidity affects only the uppermost layer of fuel. Moisture content was higher for a heavy layer than for a light layer after the same length of drying following rain.

This difference could result from several factors. First, very light layers were thinner, less compact, and probably have a timelag closer to 10 hours than 100 hours (Nelson 1969). Second, the light layers cannot retain as much rainfall and would not have as high a starting moisture content. Finally, the light layers may have a lower equilibrium moisture content (EMC) than the heavy layers.

[3] Paul, James T. 1968. Influence of rate of rainfall on pine litter moisture content. Special problem in Hydrology, Forestry 845, prepared by author for Dr. J. D. Hewlett, 16 p.

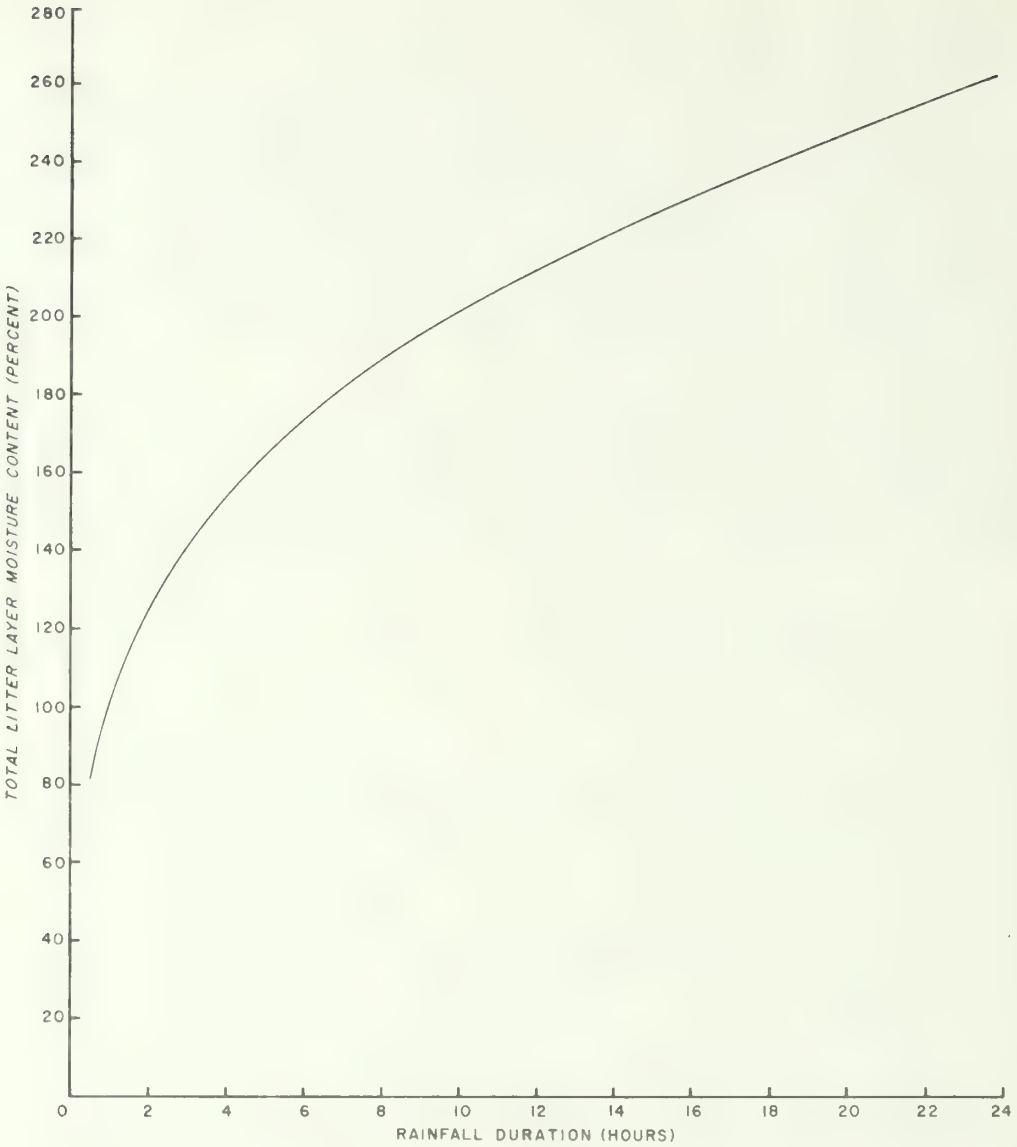

Figure 3.--Effect of precipitation duration on total litter moisture content.

Because the correlation between total layer moisture and total layer weight was highly significant, I developed more than one drying curve. In developing these curves I made a number of assumptions, some of which were best guesses. The best fit of the data through multiple-regression techniques was a straight-line decrease in moisture content following rain (fig. 4).

Since several investigators have shown that drying of forest fuels follows an exponential curve, the linearity I found must have been caused by sampling limitations. I therefore fitted exponential curves for three different total litter weight classes based on a timelag of 100 hours. For light forest litter weights (2.5 tons/acre), such as in 1- to 2-year-old roughs, an EMC of 5 percent was assumed. For moderate loadings (7 tons/acre), as in 3- to 10-year roughs, an EMC of 15 percent was assumed. For heavy fuel accumulations (12 tons/acre) representing 11- to 25-year-old roughs, a 25 percent EMC was assumed. Start-

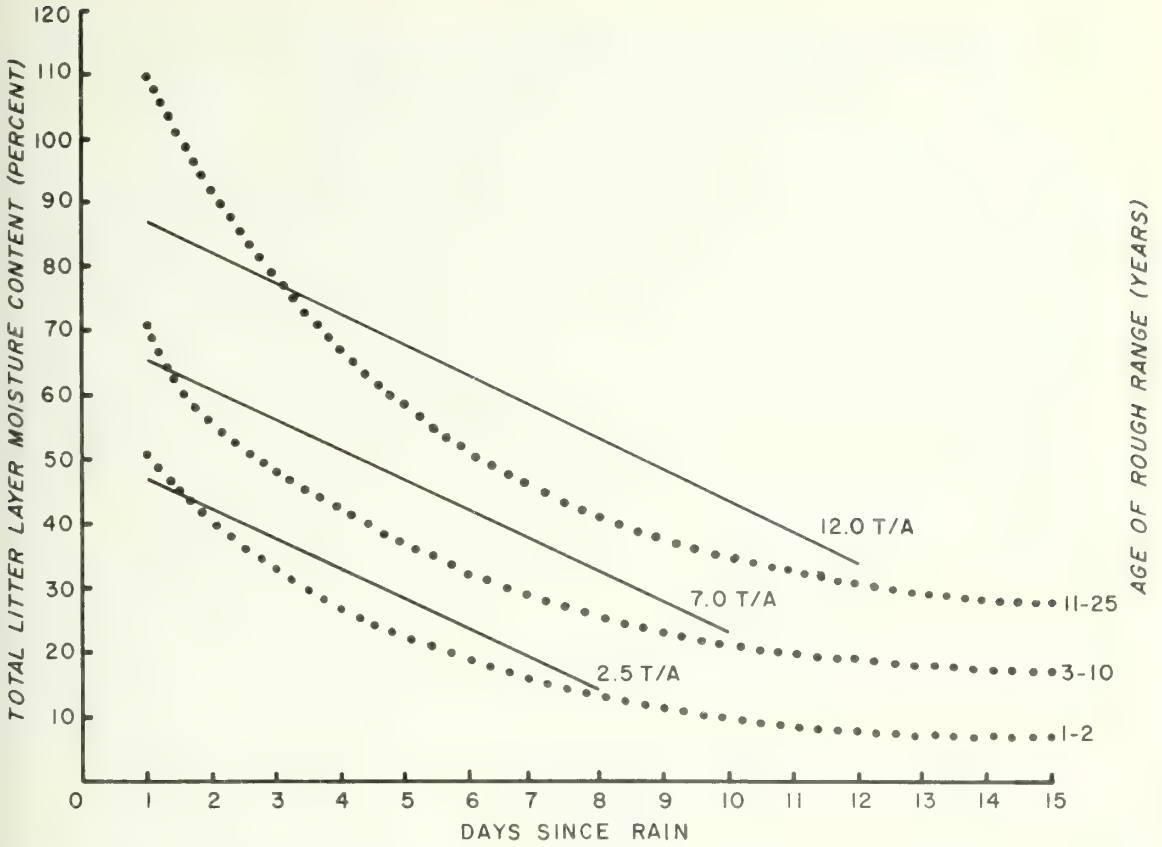

Figure 4.--Drying curves for different litter layer age classes.

ing at 250 percent moisture content, the daily drying curve was calculated from the following:

$$\frac{M_A - M_E}{M_Q - M_E} = e^{-\frac{t}{\gamma}}$$

where

M_A = average moisture content at end of period (percent)

M_E = equilibrium moisture content (percent)

M_Q = initial moisture content at start of period (percent)

e = base of Naperian logarithms (2.718)

t = time (hours)

γ = timelag constant (hours).

A portion of each calculated curve was then selected for an approximate fit of the straight-line produced by the regression equation (fig. 4). Using these curves, the decrease in total litter layer moisture content can be estimated for different ages of rough or fuel weights.

There are limitations on the accuracy of the proposed technique that should be pointed out to the fire manager. First, the method proposed here is based on a small amount of data, and many factors known to influence wetting and drying have been ignored. Second, the maximum moisture content of the total layer is somewhere between 200 and 300 percent, and an upper limit has been arbitrarily set at 250 percent. Third, young stands, very open stands, or stands that have recently been burned will have little or no F or H layer, and therefore total layer moisture content may not reach values of 250 percent. The drying curve for light fuel loading has been calculated to bring the litter layer moisture content closer to the correct values within a day or two after a long period of rainfall.

It should be remembered that fuel moisture usually varies widely from point to point in a forest stand. Therefore, values obtained by this method only roughly approximate values that may be observed at specific points in a stand.

TOTAL WEIGHT OF LITTER LAYER AND UNDERSTORY

Before available fuel can be calculated, two additional values must be estimated: total litter dry weight and total understory dry weight. McNab and Edwards (1976) have developed equations for estimating litter and understory fuel weights from stand characteristics that are relatively easy to measure.

Total litter layer weight can be estimated from age of rough and basal area of the timber stand. Total understory weight can be predicted from age of rough and average height of the understory.

These equations were developed principally from slash pine-palmetto-gallberry fuel data but included some longleaf pine-palmetto-gallberry fuel data and should apply fairly well to that complex. Loblolly pine litter layer weight is much lower than that in a slash pine stand of the same age and density. A separate estimating technique for total litter weight in loblolly stands is needed before available fuel weight can be estimated in this type, and a method is presented in the Southern Forestry Smoke Management Guidebook (SFFL Staff 1976).

DISCUSSION AND CONCLUSIONS

The equations and graphs provided here can be easily programed for computer solution. For those who want to use the method but do not have access to a computer, necessary procedures and tables are presented in the Southern Forestry Smoke Management Guidebook (SFFL Staff 1976).

An attempt was made to compare this method's fuel consumption estimates with published data. It was difficult, however, to find strictly comparable information, especially values needed as inputs for the method presented here.

Fuel consumption on a prescribed burn in a pocosin in North Carolina (Taylor and Wendel 1964) was a good example of the close approximation achieved with this method in a somewhat similar fuel situation. The area had a pond pine overstory, a 5-foot-tall shrub understory--including gallberry--that weighed 6.6 tons per acre, and a total litter weight of 6.5 tons per acre. Organic soil was present but did not burn. Total litter layer moisture content

ranged from 90 to 143 percent. Actual fuel consumption on several plots averaged 6.0 tons per acre for litter plus understory. Estimated consumption per plot ranged from 5.6 tons to 7.0 tons per acre, depending on moisture content. Thus, the estimates of total consumption were quite acceptable.

When estimates of available fuel were compared with measurements from other geographic areas, the relationship was very poor. On two plots in ponderosa pine litter (Davis and others 1968), a prescribed burn consumed 3.4 and 6.3 tons per acre. Total litter layer moisture contents were not measured and cannot be precisely calculated from the data given. They were estimated to be 13 and 17 percent for the two plots. Using these inputs, estimated litter consumption would be 6.5 tons per acre for one plot and 9.5 tons per acre for the other. Both estimates are about 3 tons per acre too high.

Data presented by Van Wagner (1972) for jack pine and mixed red and white pine stands indicated that the best predictor of available duff (F&H layers) was duff moisture content. Results are not strictly comparable because only the range and average duff weights were given. Therefore, initial weight of the layer could not be used for individual estimates. It appears that the method for southern pine stands overestimates litter consumption in northeastern pine stands by 2 to 4 tons per acre when moisture content is high and underestimates available fuel by 0.5 to 4 tons per acre when moisture content is low. Obviously, my method does not apply in these pine stands.

There are many unresolved questions concerning the estimation of available fuel weights. However, the estimating equations described in this Paper provide a reasonably accurate way to predict the amount of fuel consumed by prescribed fire in several southern forest fuel types. Under typical prescribed burning conditions (SFFL Staff 1976), the method described here provides greatly improved estimates of fuel consumption and fire effects. The use of the complete method has been described in the Southern Smoke Management Guidebook (SFFL Staff 1976). This is the best method now available for these fuel types, and it will be improved as new research findings become available.

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Aboveground Biomass of Slash Pine in a Natural Sawtimber Stand in Southern Alabama

by
Michael A. Taras
and
Douglas R. Phillips

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U.S. Department of Agriculture - Forest Service

July 1978

Southeastern Forest Experiment Station
Asheville, North Carolina

Aboveground Biomass of Slash Pine in a Natural Sawtimber Stand in Southern Alabama [1]

by

Michael A. Taras, Principal Wood Scientist

and

Douglas R. Phillips, Mensurationist
Forestry Sciences Laboratory
Athens, Georgia

Abstract.--Slash pine trees 6 to 20 inches d.b.h. selected from a natural, uneven-aged sawtimber stand in southern Alabama were sampled for green and dry weight and cubic volume in the total tree and its component parts. On the average, 84 percent of total-tree dry weight was wood, 13 percent was bark, and 3 percent was needles. The average tree sampled had 85 percent of its wood in the stem and 12 percent in the crown. Trends in biomass proportions are discussed. Specific gravity, moisture content, and green weight per cubic foot are presented for the total tree and its components. Yield tables developed from regression equations predict green and dry weights and cubic-foot volumes by d.b.h. and total height classes.

Keywords: Pinus elliottii Englem., weight, volume, prediction equations, component proportions, biomass.

This is the fourth in a series of reports on the aboveground biomass of southern pine sawtimber trees. It contains information on slash pine (Pinus elliottii Engelm.). The first three papers were on loblolly pine (Pinus taeda L.),[2] shortleaf pine (Pinus echinata Mill.),[3] and longleaf pine (Pinus palustris Mill.).[4]

This Paper reports weights and volumes of various tree components (wood, bark, crown, branches, and foliage) and presents regression equations and yield tables for predicting these components. The term "total tree" in this study refers only to the aboveground portion of the tree and does not include stump and roots.

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[1] This study was conducted by the Southeastern Forest Experiment Station in cooperation with and through the financial assistance of the Range, Timber, and Wildlife Program Area of Region 8 of the National Forest System. Field personnel were provided by the Conecuh National Forest.

[2] Taras, Michael A., and Alexander Clark III. 1975. Aboveground biomass of loblolly pine in a natural uneven-aged stand in central Alabama. TAPPI 58(2):103-105.

[3] Clark, Alexander, III, and Michael A. Taras. 1976. Biomass of shortleaf pine in a natural sawtimber stand in northern Mississippi. U. S. Dep. Agric. For. Serv., Res. Pap. SE-146, 32 p. Southeast. For. Exp. Stn., Asheville, N. C.

[4] Taras, Michael A., and Alexander Clark III. 1977. Aboveground biomass of longleaf pine in a natural sawtimber stand in southern Alabama. U.S. Dep. Agric. For. Serv., Res. Pap. SE-162, 32 p. Southeast. For. Exp. Stn., Asheville, N. C.

PROCEDURE

FIELD

A stratified random sample of 43 trees was selected from a natural, uneven-aged slash pine stand on the Conecuh National Forest in southern Alabama. Site index (age 50) averaged 74. Three to six trees from each even-inch d.b.h. class from 6 to 20 inches were selected. The sample trees averaged 12.9 inches d.b.h., 73 feet in total height, and 51 years of age. Means and ranges of the tree measurements by d.b.h. class are shown in table 1.

Table 1.--Means and ranges of measurements of slash pines in each d.b.h. class sampled

D.b.h. class (inches)	Sample trees	D.b.h.		Total height		Merchantable height[1]		Age		Form class	
		Avg.	Range	Avg.	Range	Avg.	Range	Avg.	Range	Avg.	Range
	Number	Inches		Feet				Years			
6	5	6.2	6.0- 6.4	56	47-62	2	2- 4	31	28-34	71	63-75
8	5	8.0	7.8- 8.1	58	48-68	21	15-28	39	33-58	75	69-84
10	6	10.1	9.6-10.4	66	52-77	37	30-42	40	32-66	76	69-80
12	6	12.1	11.8-12.3	74	56-85	46	32-52	61	36-68	80	77-86
14	6	14.0	13.6-14.5	75	68-80	48	38-54	48	35-62	79	76-82
16	6	16.3	16.2-16.4	86	72-99	55	46-68	64	54-67	82	79-86
18	6	18.2	18.0-18.5	86	78-94	58	46-66	62	51-68	85	78-94
20	3	20.5	20.0-21.0	81	72-91	51	40-62	61	53-68	87	83-94
All classes	43	12.9	6.0-21.0	73	47-99	40	2-68	51	28-68	79	63-94

[1] Height to 6-inch d.i.b. or merchantable top.

After felling and limbing, the main stem of each tree was bucked into merchantable saw logs and pulpwood. Saw logs 8 to 16 feet long were cut from the main stem to a 6-inch d.i.b. or merchantable top. All material above saw-log merchantability to a 2-inch top was classed as pulpwood. The crown was cut up and segregated into four categories: [1] large branches (≥2.0 inches d.o.b.), [2] medium branches (≥0.6 and ≤1.9 inches d.o.b.), [3] small branches (≤0.5 inches d.o.b.), and [4] needles. The tip of the stem (2 inches d.i.b. to top) was included in branch material in this Paper. All crown material and pulpwood were weighed in the woods to the nearest 0.25 pound. Saw logs were weighed individually on electronically operated platform scales.

Moisture content and specific gravity of wood and bark were determined from disks removed from each tree at the butt, at each saw-log bucking point, and at points where d.i.b. measured 4 and 2 inches. Disks were also randomly selected and cut from each branch category. A sample of needles was taken for determining needle moisture content. The disks were weighed and

calipered with and without bark immediately after being sawed. A representative sample of bark and wood was removed from each disk, weighed, and sealed in a polyethylene bag for laboratory analysis.

LABORATORY

Specific gravity was computed from green volume and ovendry weight. Moisture content samples were dried to a constant weight at 103° C, and moisture content was computed on an ovendry basis. Bark percentage was determined on a weight basis from cross-sectional samples. Weighted values for moisture content, specific gravity, and bark percentage in the stem, branches, and total tree were calculated by weighting disk values in proportion to the volume of the component each represented. Weighted moisture content values were used to convert component green weights to ovendry weights.

The following equation was used to calculate green weight per cubic foot separately for wood and bark on the basis of the weighted values for specific gravity and moisture content:

$$\text{Green weight per cubic foot} = 1 + \frac{M.C.}{100} \text{ (S.G.) (62.4)} \qquad (1)$$

where: M.C. = weighted tree moisture content in percent

S.G. = weighted tree specific gravity

The green cubic-foot volume of wood and bark was computed by dividing component weight by the component's green weight per cubic foot. Green cubic-foot volume of wood and bark was computed by adding the green volume of wood to the green volume of bark.

ANALYSIS

Simple linear regression analyses were applied to green and dry weight of wood, bark, and needles in the total tree and its component parts. Independent variables examined were d.b.h., total height, merchantable height, crown length, crown ratio, and form class. Regression analyses were also applied to green cubic-foot volume of wood and bark separately and in combination.

The best independent variables examined were d.b.h. and total height. Thus, tree and component weights and volumes were estimated with the equation:

$$Y = b_0 + b_1 D^2Th + e \qquad (2)$$

where: Y = weight or volume of component,

D = d.b.h. in inches,

Th = total-tree height in feet,

e = experimental error, and

b_0, b_1 = constants.

Grouping of the data into D^2Th classes indicated that the variance of Y increased with increasing D^2Th. Thus, a logarithmic transformation was used to make the variance more nearly homogeneous and meet this basic assumption of regression analysis. The final form of the equation used to predict weights and volumes was:

$$\text{Log}_{10} Y = b_0 + b_1 \text{Log}_{10} (D^2Th) \quad (3)$$

RESULTS

TOTAL-TREE BIOMASS

Green and dry weight of the total tree and proportions of tree weight in wood, bark, and needles are shown in table 2. Green weight of the total tree ranged from 357 pounds for a 6-inch tree to 6,676 pounds for a 20-inch tree. On a green-weight basis, the trees averaged 85 percent wood, 11 percent bark, and 4 percent needles; on a dry-weight basis they averaged 84 percent wood, 13 percent bark, and 3 percent needles. The proportion of tree weight in wood increased and the proportion in bark decreased as tree size increased from 6 to 12 inches d.b.h. and then remained almost constant as tree d.b.h. increased from 12 to 20 inches. The proportion of tree weight in needles did not change consistently with tree size and averaged 3 to 4 percent. Proportions of the various tree components computed on a dry-weight basis varied slightly from those computed on a green-weight basis because of differences in component moisture content (table 2).

Table 2.--Average green and dry weight of the total tree and proportion of the tree in wood, bark, and needles for slash pines 6 to 20 inches d.b.h.

D.b.h. class (inches)	Average total height	Sample trees	Total tree green weight	Tree component proportions (green)			Total tree dry weight	Tree component proportions (dry)		
				Wood	Bark	Needles		Wood	Bark	Needles
	Feet	Number	Pounds	- - Percent - -			Pounds	- - Percent - -		
6	56	5	357	79	16	5	194	78	18	4
8	58	5	650	79	16	5	360	78	17	5
10	66	6	1,140	81	13	6	622	80	15	5
12	74	6	1,852	85	12	3	1,048	83	14	3
14	75	6	2,648	83	12	5	1,424	81	14	5
16	86	6	3,764	87	10	3	2,113	86	12	2
18	86	6	5,176	87	10	3	2,872	86	11	3
20	81	3	6,676	85	10	5	3,647	84	12	4
Average	--	--	2,617	85	11	4	1,446	84	13	3

When the trees were broken down into stem and crown material, 85 percent of tree dry weight was in the stem and 15 percent was in the crown (branches plus needles) (table 3). The average crown proportion of 15 percent is slightly less than the averages previously reported in this series for loblolly pine (17 percent), shortleaf pine (18 percent), and longleaf pine (17 percent).

Table 3.--Average green and dry weight of the total tree and proportion of the tree in main stem[1] and crown (branches and needles) for slash pines 6 to 20 inches d.b.h.

D.b.h. class (inches)	Average total height	Sample trees	Total tree green weight	Tree component proportions (green)			Total tree dry weight	Tree component proportions (dry)		
				Stem	Crown			Stem	Crown	
					Branches	Needles			Branches	Needles
	Feet	Number	Pounds	- - - Percent - - -			Pounds	- - Percent - -		
6	56	5	357	86	9	5	194	88	8	4
8	58	5	650	87	8	5	360	88	8	4
10	66	6	1,140	85	9	6	622	86	9	5
12	74	6	1,852	87	10	3	1,048	88	9	3
14	75	6	2,648	82	13	5	1,424	83	12	5
16	86	6	3,764	87	10	3	2,113	88	9	3
18	86	6	5,176	84	13	3	2,872	85	12	3
20	81	3	6,676	78	18	5	3,647	79	17	4
Average	--	--	2,617	83	13	4	1,446	85	12	3

[1] Stem material to 2-inch d.i.b. top.

Proportion of tree dry weight in branches alone ranged from 8 percent in the small trees to 17 percent in the large trees and averaged 12 percent (table 3). As with the other three species, the increase in proportion of crown material was due to an increase in proportion of branch material and not to an increase in the proportion of needles.

The green and dry weight of all wood in the tree and the distribution of wood throughout the tree are presented in table 4. On the average, the trees had 90 percent of their dry wood weight in the main stem (to a 2-inch top) and 10 percent in branches. The proportion of wood in the main stem decreased and that in the branches increased as tree size increased. The increase in proportion of wood in branches was due to an increase in large branch material in larger trees. The proportion of wood in the pulpwood section of a tree decreased and proportion in the saw-log section increased as tree size increased. On the average, the trees contained 80 percent of their dry wood in saw-log material, 10 percent in pulpwood, and 10 percent in branches.

The weight and distribution of bark in the tree are presented in table 5. As tree size increased, the proportion of bark in the main stem decreased and the proportion of bark in the branches increased. This increase in bark percentage in branches was due to an increase in the proportion of large branches in large trees. On the average, 61 percent of all dry bark in the tree was in saw-log material, 12 percent was in pulpwood, and 27 percent was in branches.

CROWN BIOMASS

When the crown was analyzed as a separate entity composed of branchwood, branchbark, and needles, the proportion of crown weight in wood increased, while the proportion in needles and bark decreased with increasing tree size (table 6). On the average, 55 percent of the dry weight of the crown was in wood, 22 percent was in bark, and 23 percent was in needles.

Table 4.--Average green and dry weight of wood in the total tree and distribution of wood in main stem[1] and branches for slash pines 6 to 20 inches d.b.h.

D.b.h. class (inches)	Average total height	Sample trees	Total tree wood weight	Proportion of wood in--						
				Main stem			Branches			
				Saw log	Pulpwood	Total stem	Large	Medium	Small	All branches
	Feet	Number	Pounds	- - - - - - - - - - - - Percent - - - - - - - - - - - -						
				GREEN						
6	56	5	283	9	84	93	0	5	2	7
8	58	5	515	53	41	94	0	4	2	6
10	66	6	930	78	15	93	1	4	2	7
12	74	6	1,568	81	11	92	4	2	2	8
14	75	6	2,185	81	8	89	6	3	2	11
16	86	6	3,256	81	11	92	5	2	1	8
18	86	6	4,492	82	7	89	8	2	1	11
20	81	3	5,674	76	8	84	12	2	2	16
Average	--	--	2,223	78	11	89	6	3	2	11
				DRY						
6	56	5	152	10	84	94	0	4	2	6
8	58	5	282	55	39	94	0	4	2	6
10	66	6	500	80	13	93	1	4	2	7
12	74	6	871	83	10	93	4	2	1	7
14	75	6	1,158	82	7	89	6	3	2	11
16	86	6	1,812	82	10	92	5	2	1	8
18	86	6	2,467	85	5	90	7	2	1	10
20	81	3	3,065	78	7	85	11	3	1	15
Average	--	--	1,214	80	10	90	6	3	1	10

[1] Stem material to 2-inch d.i.b. top.

Table 5.--Average green and dry weight of bark in the total tree and distribution of bark in main stem[1] and branches for slash pines 6 to 20 inches d.b.h.

D.b.h. class (inches)	Average total height	Sample trees	Total tree bark weight	Proportion of bark in--						
				Main stem			Branches			
				Saw log	Pulpwood	Total stem	Large	Medium	Small	All branches
	Feet	Number	Pounds	- - - - - - - - - - - - Percent - - - - - - - - - - - -						
				GREEN						
6	56	5	56	8	71	79	0	11	10	21
8	58	5	101	42	36	78	0	11	11	22
10	66	6	145	61	14	75	2	11	12	25
12	74	6	226	64	11	75	8	7	10	25
14	75	6	322	59	9	68	11	8	13	32
16	86	6	392	61	12	73	10	7	10	27
18	86	6	509	59	7	66	14	7	13	34
20	81	3	698	54	8	62	18	7	13	38
Average	--	--	289	57	12	69	11	8	12	31
				DRY						
6	56	5	34	9	75	84	0	9	7	16
8	58	5	61	45	37	82	0	9	9	18
10	66	6	91	67	13	80	1	9	10	20
12	74	6	150	68	11	79	7	6	8	21
14	75	6	200	62	9	71	11	7	11	29
16	86	6	247	65	12	77	9	6	8	23
18	86	6	321	63	7	70	14	6	10	30
20	81	3	437	58	8	66	17	6	11	34
Average	--	--	182	61	12	73	10	7	10	27

[1] Stem material to 2-inch d.i.b. top.

Table 6.--Average green and dry weight of the crown and proportion of the crown in wood, bark, and needles for slash pines 6 to 20 inches d.b.h.

D.b.h. class (inches)	Average total height	Sample trees	Crown weight (green)	Crown proportion in green--			Crown weight (dry)	Crown proportion in dry--		
				Branch-wood	Branch-bark	Needles		Branch-wood	Branch-bark	Needles
	Feet	Number	Pounds	- - - Percent - - -			Pounds	- - - Percent - - -		
6	56	5	51	41	23	36	24	41	24	35
8	58	5	88	36	25	39	44	38	25	37
10	66	6	168	40	21	39	85	41	22	37
12	74	6	238	53	23	24	120	52	26	22
14	75	6	490	50	21	29	246	50	23	27
16	86	6	488	54	22	24	250	55	23	22
18	86	6	849	59	20	21	423	57	23	20
20	81	3	1,496	62	18	20	760	61	20	19
Average	--	--	432	55	21	24	218	55	22	23

When branches (wood and bark) were separated into size classes, on the average 21 percent of branch dry weight was in small branches, 25 percent was in medium branches, and 54 percent was in large branches. Across the range of tree d.b.h. classes from 6 to 20 inches, the percentage of branch material in large branches increased while the percentage in medium and small branches decreased (fig. 1). When branches were separated into wood and bark, large branches averaged 78 percent wood and 22 percent bark, medium branches averaged 73 percent wood and 27 percent bark, and small branches averaged 50 percent wood and 50 percent bark.

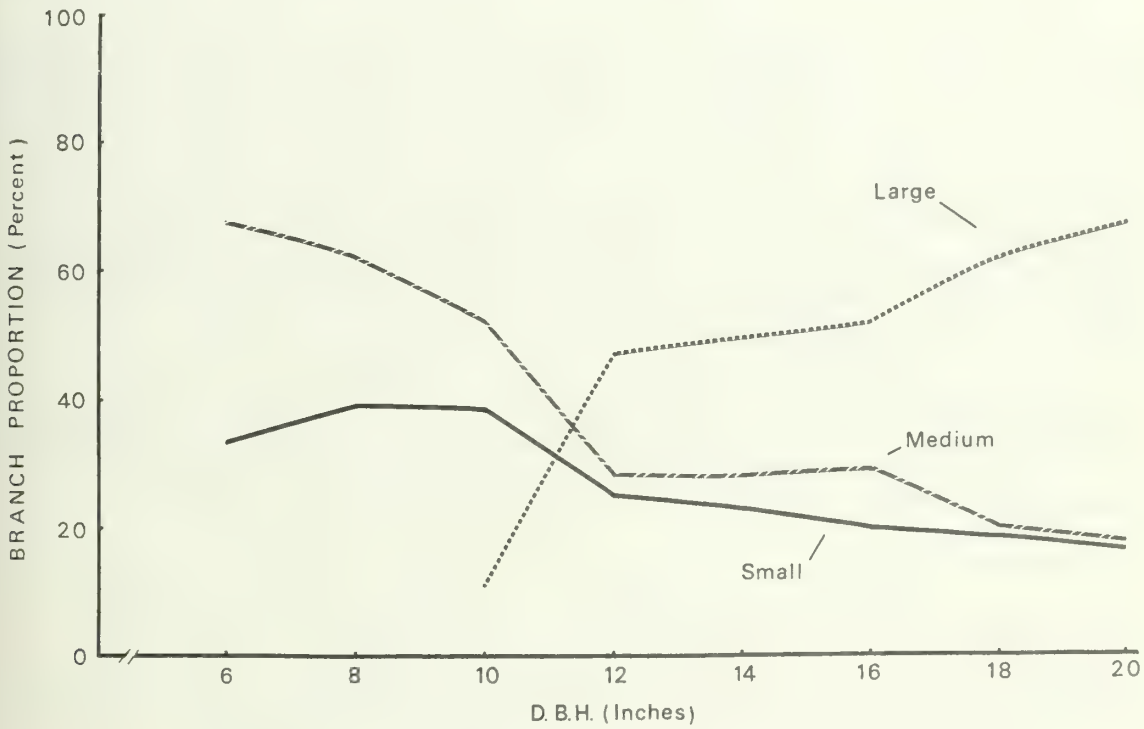

Figure 1.--Proportion of branches in crown by tree size.

MAIN STEM BIOMASS

When the main stem was analyzed separately, the proportion of stem weight in wood increased and the proportion in bark decreased as tree size increased (table 7). On the average, 89 percent of the dry weight of the stem was wood and 11 percent was bark. Similar proportions of wood and bark in the main stem were previously reported in this series for loblolly, shortleaf, and longleaf pine.

Table 7.--Average [illegible] and dry content of the stem and proportion of the stem in wood and bark for slash pines 6 to 20 inches d.b.h.

D.b.h. class (inches)	[illegible] total height	Sample trees	Main [illegible] weight (green)	Stem proportion in green--		Main stem weight (dry)	Stem proportion in dry--	
				Wood	Bark		Wood	Bark
	Feet	Number	Pounds	Percent		Pounds	Percent	
6	[illegible]	5	306	86	14	171	83	17
8	58	5	562	86	14	316	84	16
10	[illegible]	6	972	89	11	537	86	14
12	74	6	1,614	89	11	927	87	13
14	75	6	2,158	90	10	1,178	88	12
16	86	6	3,276	91	9	1,864	90	10
18	86	6	4,326	92	8	2,449	91	9
20	81	3	5,180	92	8	2,887	90	10
Average	--	--	2,185	91	9	1,228	89	11

[1] Stem material to 2-inch d.i.b. top.

PHYSICAL PROPERTIES

Wood and bark specific gravity, moisture content, and green weight per cubic foot for the total tree and its components are presented in table 8. Wood specific gravity for the total tree averaged 0.509 compared to 0.552 reported for longleaf,[4] 0.474 for loblolly,[2] and 0.472 for shortleaf.[3] Average wood specific gravity in the main stem was 0.516 or 0.037 units lower than reported by the Forest Products Laboratory.[5] Bark specific gravity was consistently lower than wood specific gravity, averaging 0.381 for the total tree, 0.373 for the main stem, and 0.402 for branches. Bark specific gravity of all slash pine tree components was higher than that reported in this series for loblolly and shortleaf pine, but lower than that reported for longleaf pine.

Wood moisture content averaged 84 percent for the total tree, 83 percent for the main stem, and 99 percent for the branches (table 8). Wood moisture content was considerably higher for pulpwood (110 percent) than that for saw logs (80 percent).

On a total-tree basis, bark moisture content averaged 59 percent, which was lower than the corresponding value for wood (84 percent) (table 8). Bark

[5] U.S. Forest Products Laboratory. 1972 (rev. 1975). Properties of major southern pines. Part I - Wood density survey, by H. E. Wahlgren and D. R. Schumann. Part II - Structural properties and specific gravity, by B. A. Bendtsen, R. L. Ethington, and W. L. Galligan. U.S. Dep. Agric. For. Serv., Res. Pap. FPL 176-177, 76 p. U.S. For. Prod. Lab., Madison, Wis.

Table 8.--Average wood and bark specific gravity, moisture content, and green weight per cubic foot for slash pine trees and tree components

Tree component	Average and standard deviation		
	Specific gravity	Moisture content	Green weight per cubic foot
		Percent	Pounds
		WOOD	
Total tree	0.509 ± 0.027	84 ± 12	58.5 ± 3.4
Saw log	.524 ± 0.031	80 ± 12	58.7 ± 3.4
Pulpwood	.461 ± 0.032	110 ± 19	60.1 ± 4.2
Main stem	.516 ± 0.028	83 ± 12	58.9 ± 3.5
Branches	.434 ± 0.024	99 ± 16	54.1 ± 4.8
		BARK	
Total tree	.381 ± 0.029	59 ± 9	37.9 ± 3.0
Saw log	.370 ± 0.037	48 ± 8	34.2 ± 3.5
Pulpwood	.394 ± 0.035	69 ± 20	41.4 ± 4.9
Main stem	.373 ± 0.034	52 ± 9	35.3 ± 3.6
Branches	.402 ± 0.039	89 ± 20	47.2 ± 4.2

moisture content was also lower for saw logs (48 percent) than for pulpwood (69 percent) or branches (89 percent). The difference in bark moisture content at different levels in the tree is due to the difference in the ratio of inner bark to outer bark with tree height.

Average wood weight per cubic foot did not vary greatly among tree components (table 8). Average green weight per cubic foot was lower for saw logs (58.7 pounds) than for pulpwood (60.1 pounds), but higher than for branchwood (54.1 pounds).

Bark was consistently lower in green weight per cubic foot than wood (table 8). Bark green weight per cubic foot averaged 37.9 pounds for the total tree, 34.2 pounds for saw logs, 41.4 pounds for pulpwood, and 47.2 pounds for branches. Branchbark weighed more per cubic foot than did the stembark because of its higher moisture content and higher specific gravity.

EQUATIONS

Biomass data for the 43 sample trees were used to develop regression equations to predict green and dry weights and cubic volumes for the total tree and its component parts (tables 9 and 10). Green and dry weight equations and associated statistics are given in table 9; green cubic-foot volume equations

Table 9.--Regression equations for estimating green and dry weight of aboveground biomass of natural slash pine trees and tree components with d.b.h. and total height as the independent variables

Weight (Y)	Regression equation[1]	Coefficient of determination (R^2)	Standard error ($S_{y \cdot x}$)
Total tree (including needles)			
Green	$\text{Log}_{10} Y = -0.88096 + 1.03014 \text{ Log}_{10}(D^2Th)$	0.99	0.042
Dry	$\text{Log}_{10} Y = -1.16061 + 1.03527 \text{ Log}_{10}(D^2Th)$	.99	.043
Total tree (excluding needles)			
Green	$\text{Log}_{10} Y = -0.93767 + 1.03929 \text{ Log}_{10}(D^2Th)$	.99	.041
Dry	$\text{Log}_{10} Y = -1.20931 + 1.04310 \text{ Log}_{10}(D^2Th)$	.99	.043
All wood in tree			
Green	$\text{Log}_{10} Y = -1.12148 + 1.06979 \text{ Log}_{10}(D^2Th)$	.99	.043
Dry	$\text{Log}_{10} Y = -1.41487 + 1.07682 \text{ Log}_{10}(D^2Th)$	.99	.045
All bark in tree [3]			
Green	$\text{Log}_{10} Y = -1.05327 + 0.84583 \text{ Log}_{10}(D^2Th)$	.96	.070
Dry	$\text{Log}_{10} Y = -1.29370 + 0.85536 \text{ Log}_{10}(D^2Th)$	.96	.072
Wood and bark in stem from stump to 6-inch d.i.b. top for trees >9.5 inches d.b.h. [4]			
Green	$\text{Log}_{10} Y = -1.15844 + 1.06520 \text{ Log}_{10}(D^2Th)$	.98	.038
Dry	$\text{Log}_{10} Y = -1.44080 + 1.07382 \text{ Log}_{10}(D^2Th)$	.98	.041
Wood in stem from stump to 6-inch d.i.b. top for trees ≥ 9.5 inches d.b.h. [4]			
Green	$\text{Log}_{10} Y = -1.31474 + 1.09224 \text{ Log}_{10}(D^2Th)$	.98	.040
Dry	$\text{Log}_{10} Y = -1.64257 + 1.10959 \text{ Log}_{10}(D^2Th)$	.98	.045
Bark in stem from stump to 6-inch d.i.b. top for trees > 9.5 inches d.b.h. [4]			
Green	$\text{Log}_{10} Y = -1.12400 + 0.81003 \text{ Log}_{10}(D^2Th)$	.93	.056
Dry	$\text{Log}_{10} Y = -1.24190 + 0.79759 \text{ Log}_{10}(D^2Th)$	.93	.056
Wood & bark in stem from stump to 2-inch d.i.b. top [3]			
Green	$\text{Log}_{10} Y = -0.91006 + 1.01913 \text{ Log}_{10}(D^2Th)$	.99	.037
Dry	$\text{Log}_{10} Y = -1.17970 + 1.02348 \text{ Log}_{10}(D^2Th)$	.99	.042

continued

Table 9.--Regression equations for estimating green and dry weight of aboveground biomass of natural slash pine trees and tree components with d.b.h. and total height as the independent variables (continued)

Weight (Y)	Regression equation [1]	Coefficient of determination (R^2)	Standard error ($S_{y.x}$) [2]
Wood in stem from stump to 2-inch d.i.b. top [3]			
Green	$\text{Log}_{10}\ Y = -1.08221 + 1.04952\ \text{Log}_{10}(D^2Th)$	0.99	0.040
Dry	$\text{Log}_{10}\ Y = -1.38111 + 1.05874\ \text{Log}_{10}(D^2Th)$	.99	.045
Bark in stem from stump to 2-inch d.i.b. top [3]			
Green	$\text{Log}_{10}\ Y = -0.93091 + 0.78051\ \text{Log}_{10}(D^2Th)$	.96	.063
Dry	$\text{Log}_{10}\ Y = -1.15366 + 0.79118\ \text{Log}_{10}(D^2Th)$	.96	.067
Crown weight (includes branchwood, branchbark, and needles) [3]			
Green	$\text{Log}_{10}\ Y = -1.91514 + 1.08130\ \text{Log}_{10}(D^2Th)$	.89	.149
Dry	$\text{Log}_{10}\ Y = -2.27828 + 1.09690\ \text{Log}_{10}(D^2Th)$	.90	.148
Needles [3]			
Green	$\text{Log}_{10}\ Y = -1.54455 + 0.84989\ \text{Log}_{10}(D^2Th)$	.76	.190
Dry	$\text{Log}_{10}\ Y = -1.90538 + 0.85834\ \text{Log}_{10}(D^2Th)$	.75	.195
Wood & bark in all branch material [3]			
Green	$\text{Log}_{10}\ Y = -2.46743 + 1.18093\ \text{Log}_{10}(D^2Th)$	.91	.149
Dry	$\text{Log}_{10}\ Y = -2.81124 + 1.19396\ \text{Log}_{10}(D^2Th)$	.91	.148
Wood in all branch material [3]			
Green	$\text{Log}_{10}\ Y = -2.93647 + 1.25648\ \text{Log}_{10}(D^2Th)$	.91	.160
Dry	$\text{Log}_{10}\ Y = -3.23700 + 1.25701\ \text{Log}_{10}(D^2Th)$	.91	.154
Bark in all branch material [3]			
Green	$\text{Log}_{10}\ Y = -2.32184 + 1.01758\ \text{Log}_{10}(D^2Th)$	.90	.136
Dry	$\text{Log}_{10}\ Y = -2.78541 + 1.06464\ \text{Log}_{10}(D^2Th)$	.89	.150

[1] $\text{Log}_{10}\ Y = b_0 + b_1\ \text{Log}_{10} D^2Th$ where:
Y = weight of tree or component in pounds
D = d.b.h. in inches
Th = total height in feet.

[2] Standard error of estimate in Log_{10} form.

[3] Regression equations based on 43 trees 6 to 21 inches d.b.h.

[4] Regression equations based on 33 trees 10 to 21 inches d.b.h.

Table 10.--Regression equations for estimating green cubic-foot volume of the aboveground biomass of natural slash pine trees and tree components with d.b.h. and total height as independent variables

Cubic-foot volume (Y)	Regression equation [1]	Coefficient of determination (R^2)	Standard error ($S_{y \cdot x}$) [2]
Total tree [3]			
Wood	$\text{Log}_{10} Y = -2.96250 + 1.08866 \text{ Log}_{10}(D^2Th)$	0.99	0.039
Bark	$\text{Log}_{10} Y = -2.80391 + 0.88891 \text{ Log}_{10}(D^2Th)$	.97	.067
Wood & Bark	$\text{Log}_{10} Y = -2.71839 + 1.05044 \text{ Log}_{10}(D^2Th)$	.99	.038
Stem from stump to 6 inches d.i.b. for trees> 9.5 inches d.b.h. [4]			
Wood	$\text{Log}_{10} Y = -3.20017 + 1.12010 \text{ Log}_{10}(D^2Th)$	.98	.042
Bark	$\text{Log}_{10} Y = -2.81940 + 0.85078 \text{ Log}_{10}(D^2Th)$	.93	.059
Wood & Bark	$\text{Log}_{10} Y = -2.95191 + 1.07898 \text{ Log}_{10}(D^2Th)$	.98	.037
Stem from stump to 2-inch d.i.b. top			
Wood	$\text{Log}_{10} Y = -2.92607 + 1.06828 \text{ Log}_{10}(D^2Th)$	.99	.037
Bark	$\text{Log}_{10} Y = -2.69982 + 0.83553 \text{ Log}_{10}(D^2Th)$	.97	.063
Wood & Bark	$\text{Log}_{10} Y = -2.68740 + 1.02867 \text{ Log}_{10}(D^2Th)$	.99	.034
All branch material [3]			
Wood	$\text{Log}_{10} Y = -4.67578 + 1.25859 \text{ Log}_{10}(D^2Th)$	.91	.153
Bark	$\text{Log}_{10} Y = -4.20359 + 1.07009 \text{ Log}_{10}(D^2Th)$	.90	.143
Wood & Bark	$\text{Log}_{10} Y = -4.22890 + 1.19310 \text{ Log}_{10}(D^2Th)$	.91	.147

[1] $\text{Log}_{10} Y = b_0 + b_1 \text{ Log}_{10} D^2Th$ where:

Y = cubic-foot volume of tree or component
D = d.b.h. in inches
Th = total height in feet.

[2] Standard error of estimate in Log_{10} form.

[3] Regression equations based on 43 trees 6 to 21 inches d.b.h.

[4] Regression equations based on 33 trees 10 to 21 inches d.b.h.

with associated statistics are given in table 10. For most equations, the coefficient of determination indicates a high degree of linear association between the independent variable (D^2Th) and component weight or volume. Poorest associations occurred in equations developed to predict branch weight and volume. Crown components varied more than other tree components.

YIELD TABLES

The equations in tables 9 and 10 were used to develop tables of biomass weight and volume. These tables of predicted yields are presented in the Appendix. Predicted green and dry weights of wood, bark, and needles in the total tree, main stem, and crown are presented in tables 11 through 21 by d.b.h. and total height classes. Predicted green cubic-foot volumes of wood and bark in the total tree, main stem, and branches are presented in tables 22 through 24.

Trees with the same d.b.h. and total height can vary considerably in weight and volume because of differences in crown size, moisture content, specific gravity, and taper. The yield tables presented in the Appendix should not be used indiscriminately over the range of slash pine without testing. Rather, they should be applied only to natural, closed stands which are similar in age, taper rate, and wood properties to the trees sampled.

APPENDIX

Table 11.--Predicted weight of total tree (wood, bark, and needles) for slash pine trees 6 to 20 inches d.b.h.[1]

D.b.h. (inches)	Total tree height (feet)[2]						
	50	60	70	80	90	100	110
	Pounds						
	GREEN[3]						
6	297	358	420	482	544	606	669
7	408	492	577	662	747	833	919
8	537	648	759	871	984	1,096	1,209
9	684	826	968	1,110	1,254	1,397	1,542
10	850	1,026	1,202	1,380	1,558	1,736	1,915
11	1,035	1,248	1,463	1,679	1,896	2,113	2,331
12	1,238	1,493	1,751	2,009	2,268	2,528	2,789
13	1,460	1,761	2,064	2,369	2,674	2,981	3,288
14	1,700	2,052	2,405	2,760	3,115	3,473	3,831
15	1,960	2,365	2,772	3,181	3,591	4,003	4,416
16	2,239	2,702	3,166	3,633	4,102	4,572	5,044
17	2,537	3,061	3,588	4,117	4,648	5,181	5,715
18	2,854	3,443	4,036	4,631	5,229	5,828	6,429
19	3,190	3,849	4,512	5,177	5,845	6,515	7,187
20	3,546	4,278	5,015	5,754	6,496	7,241	7,988
	DRY[4]						
6	162	196	229	264	298	332	366
7	223	269	316	363	410	457	504
8	294	355	416	478	540	602	665
9	375	453	531	610	689	769	848
10	466	563	661	759	857	956	1,055
11	568	686	805	924	1,044	1,165	1,285
12	680	822	964	1,107	1,250	1,394	1,539
13	803	970	1,138	1,306	1,476	1,646	1,817
14	936	1,131	1,326	1,523	1,721	1,919	2,118
15	1,080	1,304	1,530	1,757	1,985	2,213	2,443
16	1,234	1,491	1,749	2,008	2,268	2,530	2,792
17	1,400	1,690	1,983	2,277	2,572	2,868	3,166
18	1,575	1,903	2,232	2,563	2,895	3,229	3,563
19	1,762	2,128	2,496	2,866	3,238	3,611	3,986
20	1,959	2,366	2,776	3,187	3,601	4,016	4,432

[1] Blocked-in area indicates range of data.
[2] Includes 1-foot stump allowance.
[3] $\text{Log}_{10}\ Y = -0.88096 + 1.03014\ \text{Log}_{10} D^2Th.$
[4] $\text{Log}_{10}\ Y = -1.16061 + 1.03527\ \text{Log}_{10} D^2Th.$

Table 12.--Predicted weight of all aboveground wood excluding bark for slash pine trees 6 to 20 inches d.b.h.[1]

D.b.h. (inches)	Total tree height (feet)[2]						
	50	60	70	80	90	100	110
	Pounds						
	GREEN[3]						
6	230	279	329	380	431	482	534
7	319	388	458	528	599	670	742
8	425	516	609	703	797	892	988
9	547	664	784	904	1,025	1,148	1,271
10	685	832	982	1,132	1,284	1,438	1,592
11	840	1,021	1,204	1,389	1,575	1,763	1,952
12	1,012	1,230	1,450	1,673	1,897	2,124	2,352
13	1,201	1,459	1,721	1,985	2,252	2,250	2,791
14	1,407	1,710	2,017	2,326	2,639	2,953	3,270
15	1,631	1,982	2,337	2,696	3,058	3,423	3,791
16	1,872	2,276	2,683	3,096	3,511	3,930	4,352
17	2,132	2,591	3,055	3,524	3,998	4,474	4,955
18	2,409	2,928	3,453	3,983	4,518	5,057	5,599
19	2,704	3,287	3,876	4,471	5,072	5,677	6,286
20	3,018	3,668	4,326	4,990	5,660	6,335	7,015
	DRY[4]						
6	123	150	177	204	232	260	288
7	172	209	247	285	323	362	401
8	229	278	329	380	431	483	535
9	295	359	424	489	555	622	689
10	370	450	532	614	697	781	865
11	454	553	653	754	856	958	1,062
12	548	667	787	909	1,032	1,156	1,281
13	651	792	935	1,080	1,226	1,373	1,522
14	764	929	1,097	1,267	1,438	1,611	1,785
15	886	1,078	1,273	1,470	1,669	1,869	2,071
16	1,018	1,239	1,463	1,689	1,918	2,148	2,380
17	1,160	1,412	1,667	1,925	2,185	2,447	2,712
18	1,312	1,597	1,885	2,177	2,471	2,768	3,067
19	1,474	1,794	2,118	2,446	2,776	3,110	3,446
20	1,647	2,004	2,365	2,731	3,101	3,473	3,848

[1] Blocked-in area indicates range of data.

[2] Includes 1-foot stump allowance.

[3] $\text{Log}_{10}\ Y = -1.12148 + 1.06979\ \text{Log}_{10} D^2Th.$

[4] $\text{Log}_{10}\ Y = -1.41487 + 1.07682\ \text{Log}_{10} D^2Th.$

Table 13.--Predicted weight of all aboveground bark for slash pine trees 6 to 20 inches d.b.h. [1]

D.b.h. (inches)	Total tree height (feet) [2]						
	50	60	70	80	90	100	110
	Pounds						
GREEN [3]							
6	50	58	67	75	82	90	98
7	65	76	86	97	107	117	127
8	82	95	108	121	134	147	159
9	100	116	132	148	164	179	194
10	119	139	158	177	196	214	232
11	140	163	186	208	230	251	272
12	162	189	215	241	266	291	316
13	185	216	246	276	305	333	361
14	210	245	279	313	346	378	410
15	236	276	314	352	388	425	460
16	263	307	350	392	433	474	513
17	292	341	388	434	480	525	569
18	322	375	427	479	529	578	626
19	352	411	468	524	579	633	686
20	384	448	511	572	632	691	749
DRY [4]							
6	31	36	41	46	51	56	61
7	40	47	54	60	67	73	79
8	51	59	68	76	84	92	99
9	62	72	83	93	102	112	122
10	74	87	99	111	123	134	146
11	87	102	116	131	144	158	171
12	101	118	135	151	168	183	199
13	116	136	155	174	192	210	228
14	132	154	176	197	218	239	259
15	148	173	198	222	245	269	291
16	166	194	221	248	274	300	325
17	184	215	245	275	304	333	361
18	203	237	270	303	335	367	398
19	222	260	297	332	368	402	437
20	243	284	324	363	401	439	477

[1] Blocked-in area indicates range of data.

[2] Includes 1-foot stump allowance.

[3] $\text{Log}_{10}\ Y = -1.05327 + 0.84583\ \text{Log}_{10} D^2Th.$

[4] $\text{Log}_{10}\ Y = -1.29370 + 0.85536\ \text{Log}_{10} D^2Th.$

Table 14.--Predicted weight of needles for slash pine trees 6 to 20 inches d.b.h. [1]

D.b.h. (inches)	Total tree height (feet)[2]						
	50	60	70	80	90	100	110
	Pounds						
GREEN [3]							
6	17	19	22	25	27	30	33
7	22	25	29	32	36	39	42
8	27	32	36	41	45	49	53
9	33	39	44	50	55	60	65
10	40	46	53	59	65	72	78
11	47	55	62	70	77	84	91
12	54	63	72	81	89	98	106
13	62	72	83	93	102	112	121
14	70	82	94	105	116	127	138
15	79	92	105	118	130	143	155
16	88	103	118	132	146	159	173
17	98	114	130	146	161	176	191
18	108	126	144	161	178	194	211
19	118	138	157	176	195	213	231
20	129	151	172	192	213	233	252
DRY [4]							
6	8	9	10	12	13	14	15
7	10	12	13	15	17	18	20
8	13	15	17	19	21	23	25
9	16	18	21	23	26	28	31
10	19	22	25	28	31	34	37
11	22	26	29	33	36	40	43
12	25	30	34	38	42	46	50
13	29	34	39	44	48	53	57
14	33	39	44	50	55	60	65
15	37	44	50	56	62	68	73
16	42	49	56	62	69	76	82
17	46	54	62	69	77	84	91
18	51	60	68	76	85	93	100
19	56	65	75	84	93	102	110
20	61	72	82	92	101	111	120

[1] Blocked-in area indicates range of data.

[2] Includes 1-foot stump allowance.

[3] $\text{Log}_{10}\ Y = -1.54455 + 0.84989\ \text{Log}_{10} D^2Th.$

[4] $\text{Log}_{10}\ Y = -1.90538 + 0.85834\ \text{Log}_{10} D^2Th.$

Table 15.--Predicted weight of wood and bark in main stem to 2-inch d.i.b. top for slash pine trees 6 to 20 inches d.b.h.[1]

D.b.h. (inches)	Total tree height (feet)[2]						
	50	60	70	80	90	100	110
	Pounds						
	GREEN[3]						
6	256	308	360	413	465	518	571
7	350	421	493	565	637	709	781
8	459	553	647	742	836	931	1,026
9	584	703	823	943	1,063	1,184	1,304
10	724	872	1,020	1,169	1,318	1,467	1,617
11	879	1,059	1,239	1,419	1,600	1,782	1,963
12	1,050	1,264	1,479	1,695	1,911	2,127	2,344
13	1,236	1,488	1,741	1,995	2,249	2,504	2,760
14	1,437	1,731	2,025	2,320	2,616	2,913	3,210
15	1,654	1,992	2,331	2,671	3,011	3,353	3,695
16	1,887	2,272	2,659	3,046	3,435	3,824	4,214
17	2,135	2,571	3,008	3,447	3,886	4,327	4,768
18	2,399	2,889	3,380	3,873	4,367	4,861	5,357
19	2,678	3,225	3,774	4,324	4,875	5,428	5,982
20	2,973	3,580	4,190	4,800	5,413	6,026	6,641
	DRY[4]						
6	142	171	200	230	259	288	318
7	195	234	275	315	355	395	436
8	256	308	361	414	467	520	573
9	325	392	459	526	594	662	729
10	404	487	570	653	737	821	905
11	491	591	692	794	896	998	1,100
12	586	707	827	949	1,070	1,192	1,314
13	691	833	975	1,118	1,261	1,404	1,548
14	804	969	1,134	1,301	1,467	1,634	1,802
15	926	1,116	1,307	1,498	1,690	1,882	2,075
16	1,057	1,273	1,491	1,709	1,928	2,148	2,368
17	1,196	1,442	1,688	1,935	2,183	2,432	2,681
18	1,345	1,621	1,898	2,176	2,454	2,734	3,014
19	1,502	1,810	2,120	2,430	2,741	3,054	3,366
20	1,668	2,011	2,354	2,699	3,045	3,392	3,739

[1] Blocked-in area indicates range of data.

[2] Includes 1-foot stump allowance.

[3] $\text{Log}_{10}\ Y = -0.91006 + 1.01913\ \text{Log}_{10} D^2Th.$

[4] $\text{Log}_{10}\ Y = -1.17970 + 1.02348\ \text{Log}_{10} D^2Th.$

Table 17.--Predicted weight of bark in main stem to 2-inch d.i.b. top for slash pine trees 6 to 20 inches d.b.h. [1]

D.b.h. (inches)	Total tree height (feet) [2]						
	50	60	70	80	90	100	110
	Pounds						
GREEN [3]							
6	41	47	53	59	64	70	75
7	52	60	67	75	82	89	96
8	64	74	83	92	101	110	118
9	77	88	100	111	121	132	142
10	90	104	118	130	143	155	167
11	105	121	136	151	166	180	194
12	120	139	156	173	190	206	222
13	136	157	177	196	215	234	252
14	153	176	199	221	242	263	283
15	170	196	221	246	269	292	315
16	188	217	245	272	298	323	348
17	207	239	269	299	327	356	383
18	226	261	294	327	358	389	419
19	246	284	320	355	390	423	456
20	267	308	347	385	422	458	494
DRY [4]							
6	26	31	34	38	42	46	49
7	34	39	44	49	54	58	63
8	42	48	54	60	66	72	78
9	50	58	65	73	80	87	94
10	59	68	77	86	94	103	111
11	69	80	90	100	110	119	129
12	79	91	103	115	126	137	148
13	90	104	117	130	143	155	168
14	101	117	132	146	161	175	188
15	113	130	147	163	179	195	210
16	125	144	163	181	199	216	233
17	137	159	179	199	219	238	256
18	150	174	196	218	239	260	280
19	164	189	214	237	261	283	305
20	178	205	232	257	283	307	331

[1] Blocked-in area indicates range of data.

[2] Includes 1-foot stump allowance.

[3] $\text{Log}_{10}\ Y = -0.93091 + 0.78051\ \text{Log}_{10} D^2Th.$

[4] $\text{Log}_{10}\ Y = -1.15366 + 0.79118\ \text{Log}_{10} D^2Th.$

Table 16.--Predicted weight of wood excluding bark in main stem to 2-inch d.i.b. top for slash pine trees 6 to 20 inches d.b.h.[1]

D.b.h. (inches)	Total tree height (feet)[2]						
	50	60	70	80	90	100	110
	Pounds						
GREEN[3]							
6	216	261	307	354	400	447	494
7	298	361	425	489	553	618	683
8	395	478	562	647	732	817	903
9	506	612	720	828	937	1,047	1,157
10	631	764	898	1,033	1,169	1,306	1,443
11	771	933	1,097	1,262	1,428	1,595	1,763
12	925	1,120	1,317	1,515	1,714	1,915	2,116
13	1,094	1,325	1,558	1,792	2,028	2,265	2,503
14	1,278	1,548	1,820	2,094	2,369	2,646	2,924
15	1,478	1,789	2,103	2,420	2,738	3,058	3,380
16	1,692	2,049	2,409	2,771	3,135	3,502	3,870
17	1,922	2,327	2,735	3,147	3,561	3,977	4,396
18	2,166	2,623	3,084	3,548	4,015	4,484	4,956
19	2,427	2,939	3,455	3,974	4,497	5,023	5,552
20	2,703	3,273	3,847	4,426	5,009	5,594	6,183
DRY[4]							
6	116	141	166	191	217	242	268
7	161	195	230	265	300	366	371
8	214	259	305	352	398	445	493
9	274	333	392	451	511	571	632
10	343	416	490	564	639	714	790
11	420	509	599	690	782	874	967
12	504	612	720	830	940	1,051	1,162
13	598	725	853	983	1,113	1,245	1,377
14	699	848	998	1,150	1,303	1,456	1,611
15	809	981	1,155	1,331	1,508	1,685	1,864
16	928	1,125	1,325	1,526	1,728	1,932	2,137
17	1,055	1,279	1,506	1,735	1,965	2,197	2,430
18	1,190	1,444	1,700	1,958	2,218	2,480	2,743
19	1,335	1,619	1,906	2,195	2,487	2,780	3,076
20	1,488	1,805	2,125	2,447	2,772	3,099	3,428

[1] Blocked-in area indicates range of data.

[2] Includes 1-foot stump allowance.

[3] $\text{Log}_{10}\ Y = -1.08221 + 1.04952\ \text{Log}_{10} D^2Th.$

[4] $\text{Log}_{10}\ Y = -1.38111 + 1.05874\ \text{Log}_{10} D^2Th.$

Table 18.--Predicted weight of crown material (branchwood, branchbark, and needles) in slash pine trees 6 to 20 inches d.b.h.[1]

D.b.h. (inches)	Total tree height (feet)[2]						
	50	60	70	80	90	100	110
	Pounds						
GREEN[3]							
6	40	49	58	67	76	85	94
7	56	68	81	93	106	119	132
8	75	91	108	125	142	159	176
9	97	118	139	161	183	205	227
10	121	148	175	202	229	257	285
11	149	182	215	248	282	316	350
12	180	219	259	300	340	381	423
13	214	261	308	356	405	453	503
14	252	306	362	418	475	532	590
15	292	356	420	485	551	618	685
16	336	409	483	558	634	710	787
17	383	466	551	636	723	810	898
18	433	528	623	720	818	916	1,016
19	487	593	700	809	919	1,030	1,142
20	544	662	783	904	1,027	1,151	1,276
DRY[4]							
6	20	24	28	33	37	42	47
7	27	34	40	46	52	59	65
8	37	45	53	62	70	79	88
9	48	58	69	80	91	102	113
10	60	73	87	101	115	129	143
11	74	91	107	124	141	159	176
12	90	110	130	150	171	192	213
13	107	131	155	179	204	229	254
14	126	154	182	211	240	269	299
15	146	179	212	245	279	313	348
16	169	206	244	282	321	361	400
17	193	235	279	323	367	412	457
18	218	267	316	366	416	467	518
19	246	300	356	412	468	526	584
20	275	336	398	461	524	588	653

[1] Blocked-in area indicates range of data.

[2] Includes 1-foot stump allowance.

[3] $\text{Log}_{10}\ Y = -1.91514 + 1.08130\ \text{Log}_{10} D^2Th.$

[4] $\text{Log}_{10}\ Y = -2.27828 + 1.09690\ \text{Log}_{10} D^2Th.$

Table 19.--Predicted weight of wood and bark in branches for slash pine trees 6 to 20 inches d.b.h.[1]

D.b.h. (inches)	Total tree height (feet)[2]						
	50	60	70	80	90	100	110
	Pounds						
	GREEN[3]						
6	24	30	35	41	48	54	60
7	34	43	51	60	69	78	87
8	47	58	70	82	94	107	119
9	62	77	92	108	124	141	157
10	80	99	118	139	159	180	202
11	100	124	148	174	200	226	253
12	122	152	182	213	245	278	311
13	148	183	220	258	296	335	375
14	176	218	262	307	353	399	447
15	207	257	309	361	415	470	526
16	241	300	359	421	250	548	613
17	279	346	415	485	558	632	707
18	319	396	475	556	639	723	809
19	362	449	539	631	725	822	919
20	409	507	609	713	819	927	1,038
	DRY[4]						
6	12	15	18	21	24	27	30
7	17	21	26	30	35	39	44
8	24	29	35	41	48	54	61
9	31	39	47	55	63	72	80
10	40	50	60	71	81	92	103
11	51	63	76	89	102	116	130
12	62	77	93	109	126	142	160
13	75	94	113	132	152	172	193
14	90	112	134	158	182	206	231
15	106	132	159	186	214	243	272
16	124	154	185	217	260	283	317
17	143	178	214	251	289	327	367
18	164	204	245	287	331	375	420
19	187	232	279	327	376	427	478
20	211	262	315	370	425	482	541

[1] Blocked-in area indicates range of data.

[2] Includes 1-foot stump allowance.

[3] $\text{Log}_{10}\ Y = -2.46743 + 1.18093\ \text{Log}_{10} D^2Th.$

[4] $\text{Log}_{10}\ Y = -2.81124 + 1.19396\ \text{Log}_{10} D^2Th.$

Table 20.--Predicted weight of branchwood in slash pine trees 6 to 20 inches d.b.h.[1]

D.b.h. (inches)	Total tree height (feet)[2]						
	50	60	70	80	90	100	110
	Pounds						
GREEN[3]							
6	14	18	22	26	30	34	38
7	21	26	32	38	44	50	57
8	29	37	45	53	61	70	79
9	39	50	60	71	83	94	106
10	51	65	78	93	108	123	139
11	65	82	100	118	137	156	176
12	81	102	124	147	170	194	219
13	99	125	152	179	208	238	268
14	120	151	183	216	251	286	323
15	142	179	217	257	298	340	384
16	168	211	256	302	351	400	451
17	195	245	298	352	408	466	525
18	225	283	344	407	471	538	607
19	258	324	394	466	540	617	695
20	294	369	448	530	614	701	791
DRY[4]							
6	7	9	11	13	15	17	19
7	11	13	16	19	22	25	28
8	15	19	23	27	31	35	40
9	20	25	30	36	42	47	53
10	26	33	39	47	54	62	70
11	33	41	50	59	69	79	89
12	41	51	62	74	86	98	110
13	50	63	76	90	105	120	135
14	60	76	92	109	126	144	162
15	72	90	109	129	150	171	193
16	84	106	129	152	176	201	227
17	98	123	150	177	206	235	264
18	113	143	173	205	237	271	305
19	130	163	198	234	272	310	350
20	148	186	225	267	309	353	398

[1] Blocked-in area indicates range of data.

[2] Includes 1-foot stump allowance.

[3] $\text{Log}_{10}\ Y = -2.93647 + 1.25648\ \text{Log}_{10} D^2Th.$

[4] $\text{Log}_{10}\ Y = -3.23700 + 1.25701\ \text{Log}_{10} D^2Th.$

Table 21.--Predicted weight of branchbark in slash pine trees 6 to 20 inches d.b.h.[1]

D.b.h. (inches)	Total tree height (feet)[2]						
	50	60	70	80	90	100	110
	Pounds						
GREEN[3]							
6	10	12	14	16	18	20	22
7	13	16	19	22	24	27	30
8	18	21	25	28	32	36	39
9	22	27	31	36	41	45	50
10	28	33	39	45	50	56	62
11	34	40	47	54	61	68	75
12	40	48	56	65	73	81	89
13	47	57	66	76	86	96	105
14	55	66	77	89	100	111	122
15	63	76	89	102	115	128	141
16	72	87	101	116	131	146	161
17	81	98	115	131	148	165	182
18	92	110	129	148	167	185	204
19	102	123	144	165	186	207	228
20	113	137	160	183	206	230	253
DRY[4]							
6	5	6	7	8	9	10	11
7	7	8	10	11	12	14	15
8	9	11	13	15	17	18	20
9	11	14	16	19	21	24	26
10	14	17	20	23	27	30	33
11	17	21	25	29	33	36	40
12	21	25	30	35	39	44	49
13	25	30	36	41	46	52	58
14	29	35	42	48	54	61	67
15	34	41	48	56	63	70	78
16	39	47	55	64	72	81	90
17	44	53	63	73	82	92	102
18	50	60	71	82	93	104	115
19	56	68	80	92	104	117	129
20	62	75	89	103	116	130	144

[1] Blocked-in area indicates range of data.

[2] Includes 1-foot stump allowance.

[3] $\text{Log}_{10}\ Y = -2.32184 + 1.01758\ \text{Log}_{10} D^2Th.$

[4] $\text{Log}_{10}\ Y = -2.78541 + 1.06464\ \text{Log}_{10} D^2Th.$

Table 22.--Predicted green volume of wood and bark in total tree for slash pine trees 6 to 20 inches d.b.h. [1]

D.b.h. (inches)	Total tree height (feet) [2]						
	50	60	70	80	90	100	110
	Cubic feet						
	WOOD [3]						
6	3.8	4.7	5.5	6.4	7.2	8.1	9.0
7	5.3	6.5	7.7	8.9	10.1	11.3	12.6
8	7.1	8.7	10.3	11.9	13.5	15.2	16.8
9	9.2	11.2	13.3	15.4	17.5	19.6	21.8
10	11.6	14.1	16.7	19.3	22.0	24.7	27.4
11	14.3	17.4	20.6	23.8	27.1	30.4	33.7
12	17.3	21.0	24.9	28.8	32.7	36.7	40.7
13	20.5	25.0	29.6	34.3	38.9	43.7	48.4
14	24.1	29.4	34.8	40.3	45.8	51.3	56.9
15	28.0	34.2	40.4	46.8	53.2	59.6	66.2
16	32.3	39.4	46.6	53.8	61.2	68.6	76.1
17	36.8	44.9	53.1	61.4	69.8	78.3	86.9
18	41.7	50.9	60.2	69.6	79.1	88.7	98.4
19	46.9	57.2	67.7	78.3	89.0	99.8	110.7
20	52.5	64.0	75.7	87.5	99.5	111.6	123.8
	BARK [4]						
6	1.2	1.4	1.7	1.9	2.1	2.3	2.5
7	1.6	1.9	2.2	2.5	2.7	3.0	3.3
8	2.1	2.4	2.8	3.1	3.5	3.8	4.1
9	2.5	3.0	3.4	3.8	4.3	4.7	5.1
10	3.0	3.6	4.1	4.6	5.1	5.6	6.1
11	3.6	4.2	4.9	5.5	6.1	6.7	7.3
12	4.2	5.0	5.7	6.4	7.1	7.8	8.5
13	4.9	5.7	6.6	7.4	8.2	9.0	9.8
14	5.5	6.5	7.5	8.4	9.4	10.3	11.2
15	6.3	7.4	8.5	9.5	10.6	11.6	12.6
16	7.0	8.3	9.5	10.7	11.9	13.0	14.2
17	7.8	9.2	10.6	11.9	13.2	14.5	15.8
18	8.7	10.2	11.7	13.2	14.6	16.1	17.5
19	9.5	11.2	12.9	14.5	16.1	17.7	19.2
20	10.5	12.3	14.1	15.9	17.6	19.4	21.1

continued

Table 22.--Predicted green volume of wood and bark in total tree for slash pine trees 6 to 20 inches d.b.h.[1] (continued)

D.b.h. (inches)	Total tree height (feet)[2]						
	50	60	70	80	90	100	110
	Cubic feet						
	WOOD AND BARK[5]						
6	5.0	6.1	7.2	8.2	9.3	10.4	11.5
7	6.9	8.4	9.9	11.4	12.9	14.4	15.9
8	9.2	11.1	13.1	15.1	17.0	19.0	21.1
9	11.8	14.3	16.8	19.3	21.8	24.4	27.0
10	14.7	17.8	20.9	24.1	27.2	30.4	33.6
11	18.0	21.7	25.6	29.4	33.3	37.2	41.1
12	21.6	26.1	30.7	35.3	40.0	44.6	49.3
13	25.5	30.9	36.3	41.8	47.3	52.8	58.4
14	29.8	36.1	42.4	48.8	55.2	61.7	68.2
15	34.4	41.7	49.0	56.4	63.9	71.3	78.8
16	39.4	47.8	56.2	64.6	73.1	81.7	90.3
17	44.8	54.3	63.8	73.4	83.1	92.8	102.6
18	50.5	61.2	71.9	82.8	93.7	104.6	115.7
19	56.6	68.5	80.6	92.7	104.9	117.2	129.6
20	63.0	76.3	89.8	103.3	116.9	130.6	144.3

[1] Blocked-in area indicates range of data.
[2] Includes 1-foot stump allowance.
[3] $\text{Log}_{10}\ Y = -2.96250 + 1.08866\ \text{Log}_{10} D^2Th.$
[4] $\text{Log}_{10}\ Y = -2.80391 + 0.88891\ \text{Log}_{10} D^2Th.$
[5] $\text{Log}_{10}\ Y = -2.71839 + 1.05044\ \text{Log}_{10} D^2Th.$

Table 23.--Predicted green volume of wood and bark in main stem to 2-inch d.i.b. top for slash pine trees 6 to 20 inches d.b.h. [1]

D.b.h. (inches)	Total tree height (feet) [2]						
	50	60	70	80	90	100	110
	Cubic feet						
	WOOD [3]						
6	3.6	4.3	5.1	5.9	6.7	7.5	8.3
7	4.9	6.0	7.1	8.2	9.3	10.4	11.5
8	6.6	8.0	9.4	10.9	12.3	13.8	15.3
9	8.5	10.3	12.1	14.0	15.9	17.8	19.7
10	10.6	12.9	15.2	17.5	19.9	22.2	24.6
11	13.0	15.8	18.6	21.5	24.4	27.3	30.2
12	15.7	19.0	22.4	25.9	29.3	32.8	36.3
13	18.6	22.6	26.6	30.7	34.8	38.9	43.1
14	21.8	26.4	31.2	36.0	40.8	45.6	50.5
15	25.2	30.6	36.1	41.7	47.2	52.9	58.5
16	28.9	35.2	41.5	47.8	54.2	60.7	67.2
17	32.9	40.0	47.2	54.4	61.7	69.1	76.5
18	37.2	45.2	53.3	61.5	69.8	78.1	86.4
19	41.8	50.8	59.9	69.0	78.3	87.6	97.0
20	46.6	56.7	66.8	77.0	87.4	97.8	108.3
	BARK [4]						
6	1.0	1.2	1.4	1.6	1.7	1.9	2.0
7	1.4	1.6	1.8	2.0	2.2	2.4	2.6
8	1.7	2.0	2.2	2.5	2.8	3.0	3.3
9	2.1	2.4	2.7	3.1	3.4	3.7	4.0
10	2.5	2.9	3.3	3.6	4.0	4.4	4.8
11	2.9	3.4	3.8	4.3	4.7	5.1	5.6
12	3.3	3.9	4.4	4.9	5.4	6.0	6.4
13	3.8	4.4	5.0	5.6	6.2	6.8	7.4
14	4.3	5.0	5.7	6.4	7.1	7.7	8.3
15	4.8	5.6	6.4	7.2	7.9	8.6	9.4
16	5.4	6.3	7.1	8.0	8.8	9.6	10.4
17	6.0	7.0	7.9	8.8	9.8	10.7	11.5
18	6.6	7.6	8.7	9.7	10.7	11.7	12.7
19	7.2	8.4	9.5	10.6	11.7	12.8	13.9
20	7.8	9.1	10.4	11.6	12.8	14.0	15.1

continued

Table 23.--Predicted green volume of wood and bark in main stem to 2-inch d.i.b. top for slash pine trees 6 to 20 inches d.b.h.[1] (continued)

D.b.h. (inches)	Total tree height (feet)[2]						
	50	60	70	80	90	100	110
	Cubic feet						
	WOOD AND BARK[5]						
6	4.6	5.5	6.5	7.4	8.4	9.4	10.3
7	6.3	7.6	8.9	10.2	11.5	12.8	14.2
8	8.3	10.0	11.7	13.4	15.2	16.9	18.6
9	10.6	12.7	14.9	17.1	19.3	21.5	23.8
10	13.1	15.8	18.5	21.3	24.0	26.7	29.5
11	16.0	19.2	22.5	25.9	29.2	32.5	35.9
12	19.1	23.0	27.0	30.9	34.9	38.9	42.9
13	22.5	27.1	31.8	36.5	41.2	45.9	50.6
14	26.2	31.6	37.0	42.5	48.0	53.4	59.0
15	30.2	36.4	42.7	49.0	55.3	61.6	67.9
16	34.5	41.6	48.7	55.9	63.1	70.3	77.6
17	39.1	47.1	55.2	63.3	71.5	79.7	87.9
18	43.9	53.0	62.1	71.2	80.4	89.6	98.9
19	49.1	59.2	69.4	79.6	89.9	100.2	110.5
20	54.6	65.8	77.1	88.5	99.9	111.3	122.8

[1] Blocked-in area indicates range of data.
[2] Includes 1-foot stump allowance.

[3] $\text{Log}_{10}\ Y = -2.92607 + 1.06828\ \text{Log}_{10} D^2Th.$

[4] $\text{Log}_{10}\ Y = -2.69982 + 0.83553\ \text{Log}_{10} D^2Th.$

[5] $\text{Log}_{10}\ Y = -2.68740 + 1.02867\ \text{Log}_{10} D^2Th.$

Table 24.--Predicted green volume of wood and bark in branches for slash pine trees 6 to 20 inches d.b.h. [1]

D.b.h. (inches)	Total tree height (feet) [2]						
	50	60	70	80	90	100	110
	Cubic feet						
	WOOD [3]						
6	0.3	0.3	0.4	0.5	0.6	0.6	0.7
7	.4	.5	.6	.7	.8	.9	1.0
8	.5	.7	.8	1.0	1.1	1.3	1.5
9	.7	.9	1.1	1.3	1.5	1.8	2.0
10	1.0	1.2	1.5	1.7	2.0	2.3	2.6
11	1.2	1.5	1.9	2.2	2.5	2.9	3.3
12	1.5	1.9	2.3	2.7	3.2	3.6	4.1
13	1.8	2.3	2.8	3.3	3.9	4.4	5.0
14	2.2	2.8	3.4	4.0	4.7	5.3	6.0
15	2.6	3.3	4.0	4.8	5.5	6.3	7.1
16	3.1	3.9	4.8	5.6	6.5	7.5	8.4
17	3.6	4.6	5.5	6.6	7.6	8.7	9.8
18	4.2	5.3	6.4	7.6	8.8	10.0	11.3
19	4.8	6.0	7.3	8.7	10.1	11.5	13.0
20	5.5	6.9	8.3	9.9	11.4	13.1	14.7
	BARK [4]						
6	0.2	0.2	0.3	0.3	0.4	0.4	0.4
7	.3	.3	.4	.4	.5	.6	.6
8	.4	.4	.5	.6	.7	.7	.8
9	.5	.6	.7	.8	.9	1.0	1.1
10	.6	.7	.8	.9	1.1	1.2	1.3
11	.7	.8	1.0	1.2	1.3	1.5	1.6
12	.8	1.0	1.2	1.4	1.6	1.8	2.0
13	1.0	1.2	1.4	1.6	1.9	2.1	2.3
14	1.2	1.4	1.7	1.9	2.2	2.5	2.7
15	1.4	1.6	1.9	2.2	2.5	2.8	3.1
16	1.6	1.9	2.2	2.6	2.9	3.3	3.6
17	1.8	2.2	2.5	2.9	3.3	3.7	4.1
18	2.0	2.4	2.9	3.3	3.8	4.2	4.6
19	2.2	2.7	3.2	3.7	4.2	4.7	5.2
20	2.5	3.0	3.6	4.1	4.7	5.3	5.8

continued

Table 24.--Predicted green volume of wood and bark in branches for slash pine trees 6 to 20 inches d.b.h.[1] (continued)

D.b.h. (inches)	Total tree height (feet)[2]						
	50	60	70	80	90	100	110
	Cubic feet						
	WOOD AND BARK[5]						
6	0.5	0.6	0.7	0.8	0.9	1.0	1.2
7	.7	.8	1.0	1.1	1.3	1.5	1.7
8	.9	1.1	1.3	1.6	1.8	2.1	2.3
9	1.2	1.5	1.8	2.1	2.4	2.7	3.0
10	1.5	1.9	2.3	2.7	3.1	3.5	3.9
11	1.9	2.4	2.9	3.4	3.9	4.4	4.9
12	2.4	2.9	3.5	4.1	4.8	5.4	6.1
13	2.9	3.6	4.3	5.0	5.8	6.5	7.3
14	3.4	4.2	5.1	6.0	6.9	7.8	8.7
15	4.0	5.0	6.0	7.0	8.1	9.2	10.3
16	4.7	5.8	7.0	8.2	9.5	10.7	12.0
17	5.4	6.7	8.1	9.5	10.9	12.4	13.9
18	6.2	7.7	9.3	10.9	12.5	14.2	15.9
19	7.1	8.8	10.6	12.4	14.3	16.2	18.1
20	8.0	9.9	11.9	14.0	16.1	18.3	20.5

[1] Blocked-in area indicates range of data.

[2] Includes 1-foot stump allowance.

[3] $\text{Log}_{10}\ Y = -4.67578 + 1.2\ 859\ \text{Log}_{10} D^2Th.$

[4] $\text{Log}_{10}\ Y = -4.20359 + 1.07009\ \text{Log}_{10} D^2Th.$

[5] $\text{Log}_{10}\ Y = -4.22890 + 1.19310\ \text{Log}_{10} D^2Th.$

Taras, Michael A., and Douglas R. Phillips
1978. Aboveground biomass of slash pine in a natural sawtimber stand in southern Alabama. U.S. Dep. Agric. For. Serv., Res. Pap. SE-188, 31 p. Southeast. For. Exp. Stn., Asheville, N. C.

Slash pine trees 6 to 20 inches d.b.h. selected from a natural, uneven-aged sawtimber stand in southern Alabama were sampled for green and dry weight and cubic volume in the total tree and its component parts. Specific gravity, moisture content, and green weight per cubic foot are presented for the total tree and its components. Yield tables developed from regression equations predict green and dry weights and cubic-foot volumes by d.b.h. and total height classes.

Keywords: Pinus elliottii Engelm., weight, volume, prediction equations, component proportions, biomass.

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Keywords: Pinus elliottii Engelm., weight, volume, prediction equations, component proportions, biomass.

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Moisture Content of a Joist Floor Over a Crawl Space

by John E. Duff

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Throughout this paper, values are in English units because these are commonly used in the lumber and construction industries in the United States. Factors for converting from English to metric units are provided below:

To convert from	To	Multiply by
feet	meters	0.3048
inches	centimeters	2.5400

July 1978

Southeastern Forest Experiment Station
Asheville, North Carolina

Moisture Content of a Joist Floor Over a Crawl Space

by

John E. Duff, Wood Scientist
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Abstract.--In an experimental joist floor over a damp crawl space, the use of insulation did not increase the moisture content of the floor above normal levels. Vapor barriers installed on the bottoms of the joists kept the joists and floor sheathing dry during summer and winter. Vapor barriers positioned over the tops of the joists kept the floor sheathing dry, but the moisture content of the joists rose to 20 percent during the summer. In mild climates, foundation vents in houses with such a floor system can be closed during the winter and summer to conserve energy if the soil is fully covered to prevent moisture accumulation.

KEYWORDS: Insulation, wood moisture, dampness, floor sheathing, vapor barriers, moisture sensors.

The high cost of energy for home heating and cooling is prompting many homeowners to increase their house insulation. They realize that a well-insulated home improves personal comfort, saves energy, and lowers operating costs.

In the South, builders have generally not insulated floors over crawl spaces except in all-electric houses. With today's emphasis on energy conservation, many homeowners are asking about the benefits of adding insulation to such floors. Will the insulation keep their floors warmer in winter? Will moisture from the crawl space cause decay hazards in insulated floors? Should homeowners use a vapor barrier when insulating floors? Can foundation vents be closed to conserve energy during winter without moisture accumulations?

This report will help answer these and other questions for the interested homeowner.

METHODS

TEST HOUSE

Researchers conducted this study in the Whitehall environmental test house operated by the Southeastern Forest Experiment Station in Athens, Georgia. The test house (fig. 1), 24 by 24 feet, is in an open, unshaded, well-drained area on a gently sloping hillside. The house has three 8- by 16-inch foundation wall vents that meet the ventilation requirements of the Minimum Property Standards.[1]

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[1]U.S. Department of Housing and Urban Development. 1966. Minimum property standards. U.S. Dep. Housing & Urban Dev., Washington, D.C., p. 41.

Figure 1.--The Whitehall test house in Athens, Georgia, with the crawl-space floor constructed across the rear third of the structure.

EXPERIMENTAL FLOOR SYSTEM

An 8- by 24-foot joist floor system was constructed across the north end of the test structure. A concrete-block foundation wall separates the 8- by 24-foot crawl space from the rest of the underfloor space. The height of the crawl space varies from 29 to 33 inches from the soil to the bottom of the floor joists. Above the floor an interior partition divides the 8- by 24-foot room from the remainder of the above-floor space. Technicians divided the floor of this room into five structurally independent sections, each 4 feet and 9 inches wide by 8 feet long; the crawl space was not divided. Each floor section was constructed with four nominal 2- by 8-inch joists of southern pine, 16 inches on center, running in the 8-foot direction. Researchers overlaid the joists with 5/8-inch sheathing-grade plywood of southern pine. Over the sheathing, they nailed 3/4-inch strips of oak flooring. No cross-bracing was used between joists.

Figure 2 shows how researchers constructed the individual floor sections with various combinations of vapor barriers and thermal insulation. Sometimes only one or the other was used. Section 1 contained no vapor barrier or insulation; section 2 had insulation but no vapor barrier; and section 3 had insulation plus a polyethylene vapor barrier stapled over the bottom edge of the joists. Section 4 contained insulation and a vapor barrier over the top of the joists, next to the bottom side of the sheathing. Section 5 had no insulation but did have a vapor barrier positioned over the top of the joists.

Fiberglass insulation (4 inches thick) was used in batt form, without an integral vapor barrier. The vapor barrier, when used, was 0.006-inch black polyethylene

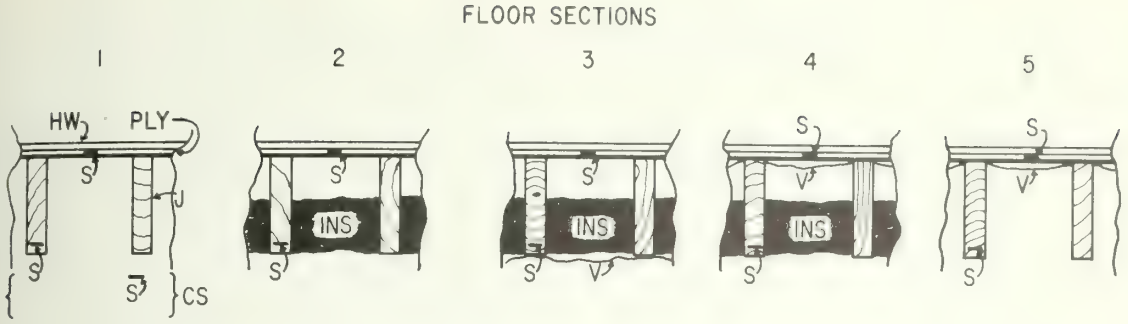

Figure 2.--Cross-sections of the joist floor sections showing general location of the moisture and temperature sensors (S), vapor barriers (V), thermal insulation (INS), hardwood floor (HW), plywood sheathing (PLY), wood joists (J), and crawl space (CS).

MOISTURE AND TEMPERATURE MEASUREMENT

Figure 2 also shows the general locations of wood moisture sensors used to measure the moisture content of the floor system. For each test section, three moisture sensors were hung in the air of the crawl space, two were located in the joists, and two were located in the plywood sheathing.

Temperature readings for each moisture sensor were needed in order to correct the temperature effect on the sensors' electrical resistance. A copper constantan thermocouple beside each moisture sensor provided temperature data. After researchers installed the five floor sections, they routed the lead wires for the moisture and temperature sensors to the edge of the floor system and through a hole into the interior of the structure. They then connected the lead wires to an automatic system where the data were collected periodically on punched paper tape.

EXPERIMENTAL PROCEDURE

The interior temperature of the house was kept at $75^{\circ} \pm 5^{\circ}$ F throughout the 2-year test period. A window-mounted heat pump heated and cooled the house. During the winters, a floor-type humidifier controlled the relative humidity at 30 ± 5 percent in the room above the crawl space. During the summers, the relative humidity was not controlled, but the dehumidifying action of the heat pump kept the relative humidity at about 70 percent. The test house was unoccupied during the 2-year study except for the visits of the research staff to collect data tapes. The structure has no plumbing fixtures that would influence the relative humidity of the interior.

The study began in January 1971 and continued through November 1972. From January to November 1971, the entire soil area in the crawl space was covered with a 0.006-inch polyethylene sheet. Researchers loosely fitted the edges of this soil cover against the lower sides of the concrete block foundation. All perimeter vents were closed but not sealed. From mid-November 1971 to September 1972, the soil cover was removed and the perimeter vents were opened. During the final 3 months of the study, the vents were closed, but the soil cover was not replaced.

WHAT IS THE MAXIMUM RELATIVE HUMIDITY TYPICALLY FOUND IN A CRAWL SPACE AND WHEN DOES IT OCCUR?

Relative humidity of the air in the crawl space reached a maximum of 95 percen twice during the study; both peaks occurred when the foundation vents were open and the soil was left exposed. Figure 3 shows that the first humidity peak occurred during January, while the second peak was recorded in the latter part of July.

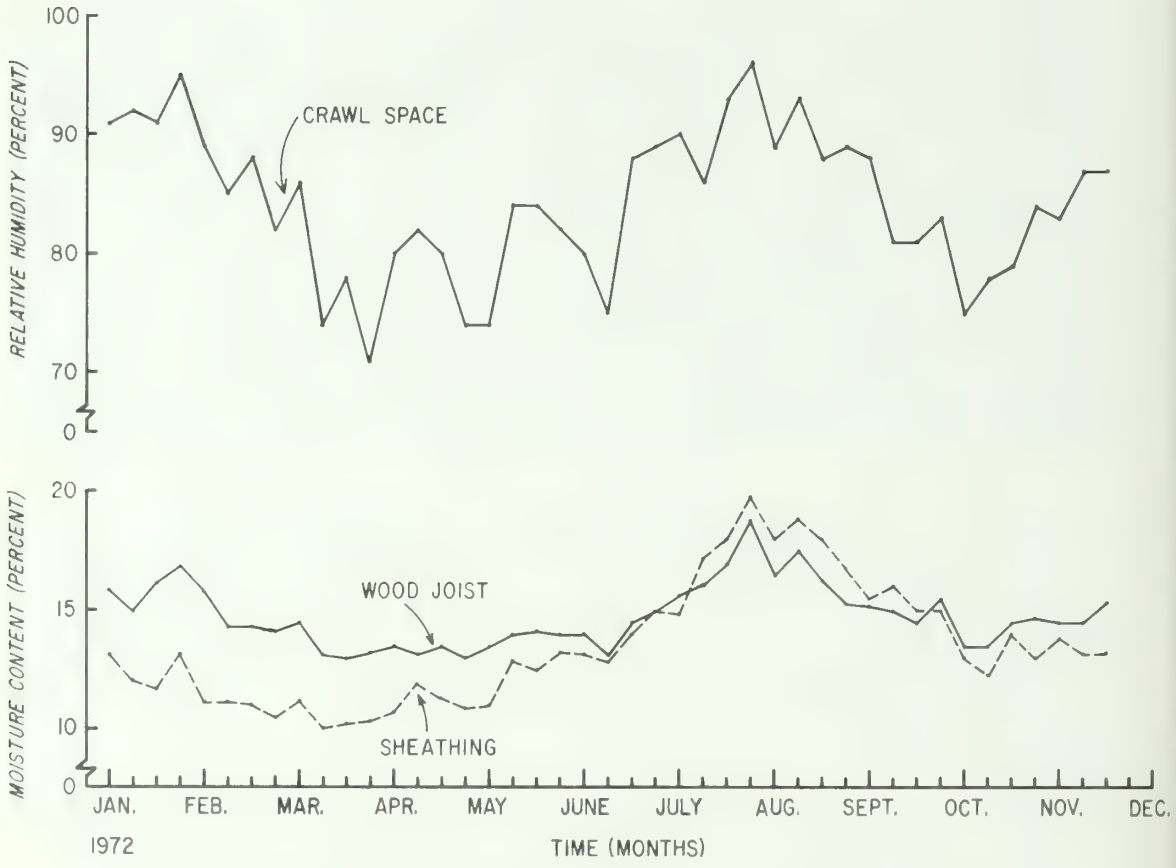

Figure 3.--A 12-month plot of relative humidity in the crawl space and the moisture content of the wood joists and sheathing of an uninsulated test floor, with vents open and no soil cover (floor section 1).

In mild climates, relative humidity of a crawl space is normally lowest during the winter. The high relative humidity observed during January resulted from moisture being introduced into the air of the crawl space when the soil cover was removed, as will be discussed later.

In mild climates, the highest relative humidity usually occurs in mid-summer. Although the humidity of the crawl space in the test house varied during the late

winter and early spring, the trend was upward to a 95-percent level in late July. Since the maximum relative humidity occurs in mid-summer, homeowners should expect floors over crawl spaces without soil covers to reach their highest moisture condition during this period.

HOW DOES RELATIVE HUMIDITY IN A CRAWL SPACE AFFECT MOISTURE CONDITIONS IN AN UNINSULATED JOIST FLOOR?

Figure 3 also shows a plot of the moisture conditions in the wood joists and sheathing of an uninsulated floor section. Except for January and February, the moisture content of the floor increased in direct response to the increase in relative humidity of the air under the floor. When the relative humidity began dropping in late summer, so did the moisture content of the floor.

Although moisture in the wood joists and floor sheathing followed the same general trends, in late winter moisture content was noticeably lower in the sheathing than in the joists, probably because of the dry air above the floor. Most homeowners have noted how dry the interior of a heated home gets during winter. In the test house, the low relative humidity in the interior caused a drying effect in the sheathing but not in the wood joists, which were more exposed to the air in the crawl space.

Moisture content during July was slightly higher in the sheathing than in the joists, probably because of the effect of air conditioning on the floor. Air conditioning the interior of the structure tended to cool the uninsulated floor slightly below the temperature in the crawl space, causing a slightly higher relative humidity around the sheathing and perhaps accounting for its higher moisture content.

WHAT MAXIMUM MOISTURE CONTENT SHOULD BE EXPECTED IN A JOIST FLOOR OVER A BARE CRAWL SPACE WITH FOUNDATION VENTS OPEN?

The lower plot in figure 3 shows that the moisture content of the floor sheathing over a bare crawl space with open vents peaked at 20 percent during the latter part of July. This is about the lowest moisture content at which some species of decay and mold fungi can survive. Since the sheathing remained at this moisture content only briefly, no decay hazard existed. However, in extremely damp crawl spaces with standing water, moisture content of the sheathing would remain at 20 percent and higher for long periods and would result in a definite decay hazard.

In most instances, homeowners can expect the joists to peak at the same moisture content as the sheathing. In the test house, the moisture content of the joists peaked at 19 percent in July, the same time as the peak for sheathing.

DOES CLOSING FOUNDATION VENTS TO CONSERVE ENERGY CAUSE HIGHER-THAN-NORMAL FLOOR MOISTURE?

Figure 4 shows that the homeowner can close the crawl-space vents in winter and summer without causing higher-than-normal floor moisture if the soil is fully covered. Note that the relative humidity under the floor varied considerably during the year but that it tended to be lower in the winter and higher in the summer.

The lower relative humidity under the floor in winter caused the moisture content of the floor joists and sheathing to remain in the 10- to 12-percent range. During the summer, the moisture content of the floor increased to 18 to 20 percent in response to the higher humidity in the crawl space.

BY REMOVING THE SOIL COVER, WILL THE DAMP SOIL IN THE CRAWL SPACE RAISE THE MOISTURE CONTENT OF THE FLOOR?

If a soil cover is removed from the crawl space, the moisture accumulated under the cover will begin to evaporate into the air of the crawl space. Figure 5 shows that removal of the soil cover will slightly increase the moisture content of a joist floor but not enough to be of concern to the homeowner. In many instances, the soil is extremely damp after removal of a soil cover. When the soil cover in the test house was removed, the foundation vents were opened. Note that the relative humidity increased sharply after removal of the soil cover but that the floor was slow to respond to the higher humidities. After a 2-week delay, moisture content of the floor increased from 14 to 17 percent and the sheathing increased from 12 to 15 percent. These higher levels of floor moisture gradually decreased, however, and the relative humidity also decreased as the soil in the crawl space dried. By March, the relative humidity and floor moisture had returned to their normal early-spring lows.

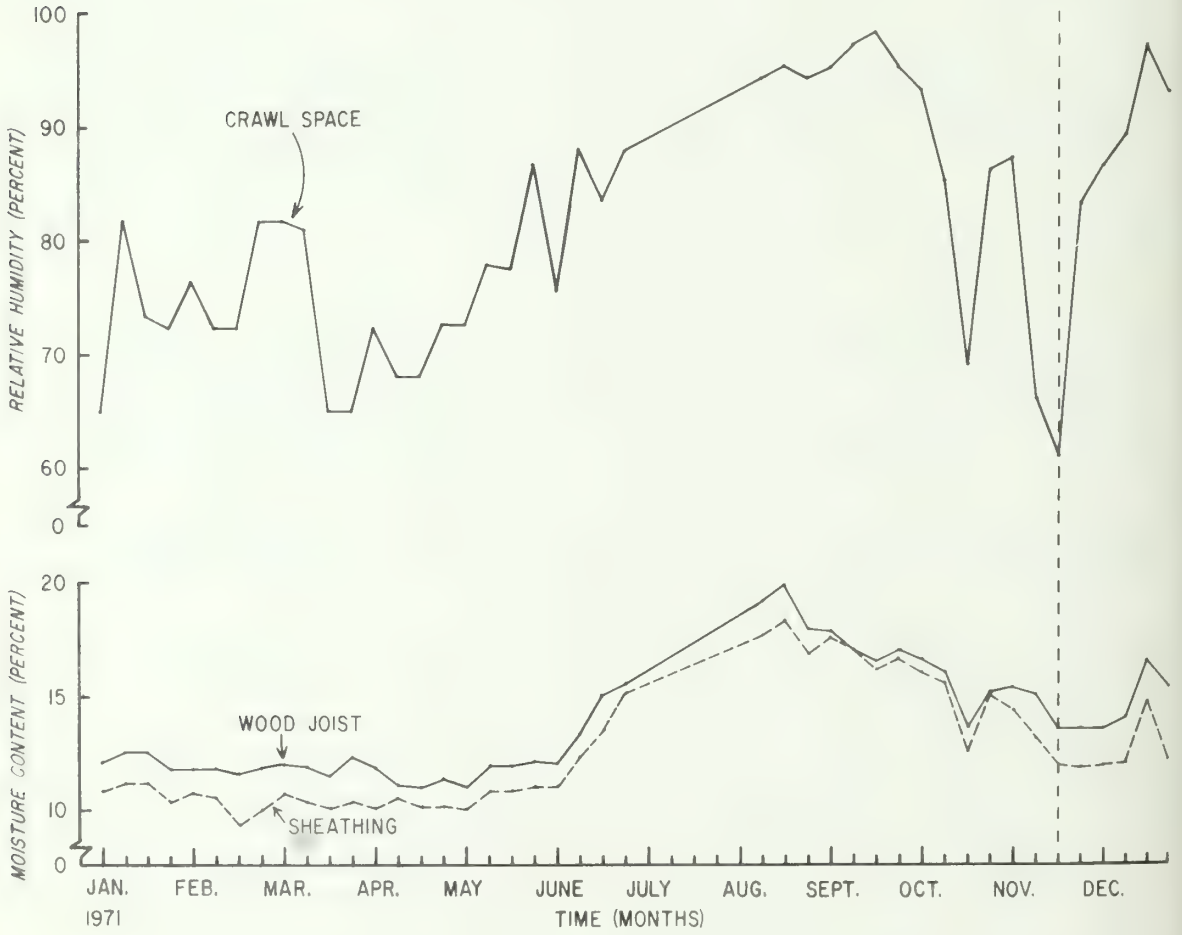

Figure 4.--A 12-month plot of relative humidity in the crawl space and the moisture content of the wood joists and sheathing of an uninsulated test floor, with a soil cover and vents closed (floor section 1). Dashed vertical line indicates the point at which the soil cover was removed and the vents were opened.

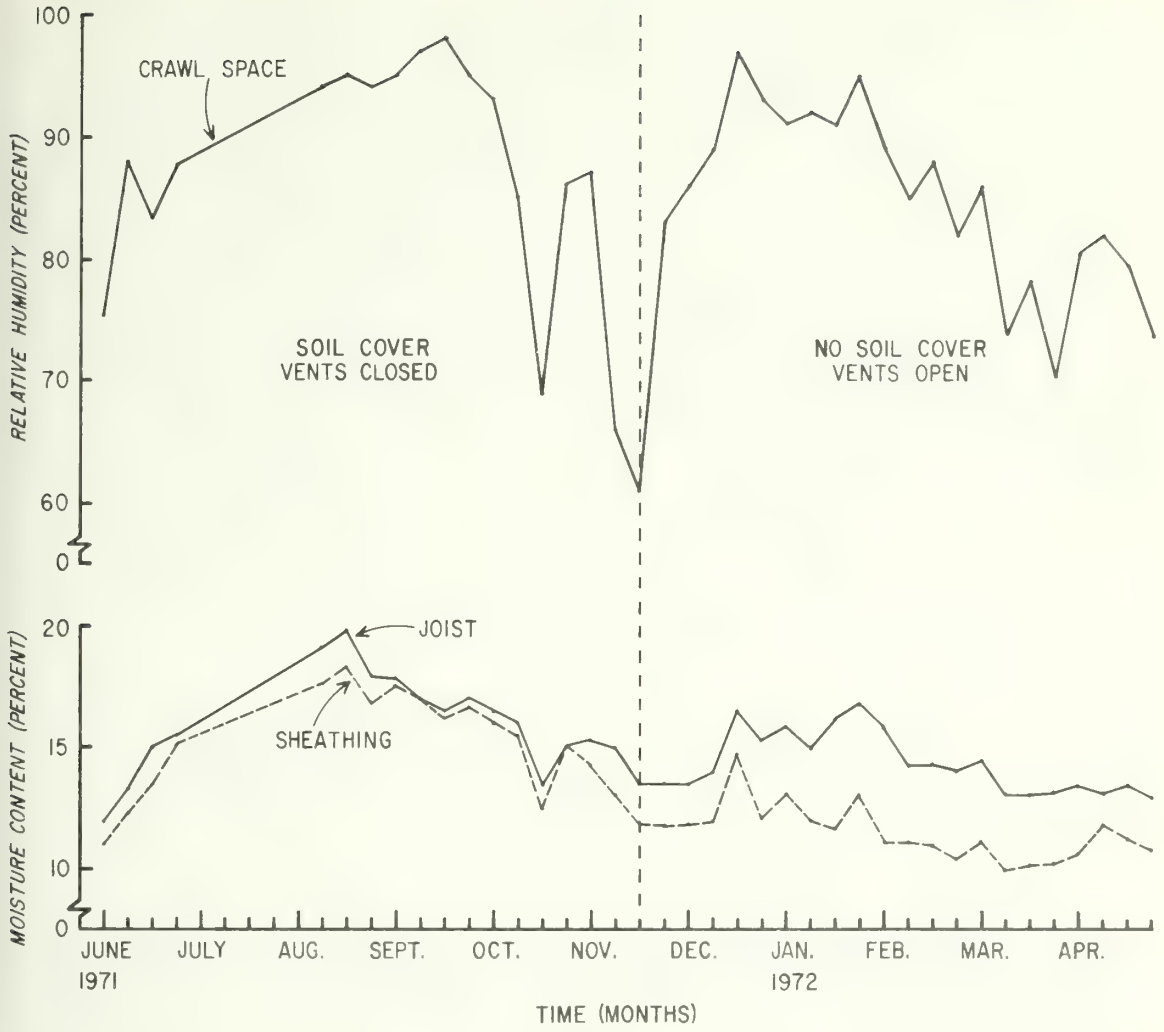

Figure 5.--An 11-month plot of relative humidity in the crawl space and moisture content of the joists and sheathing of an uninsulated floor, before and after removal of the soil cover and opening the vents (floor section 1).

HOW CAN UNINSULATED FLOOR SHEATHING OVER A CRAWL SPACE BE KEPT DRY ALL YEAR?

In uninsulated floors, the plywood sheathing can be kept at a uniformly low moisture content year-round simply by placing a vapor barrier on or near its bottom surface. As previously noted, in mild climates the high moisture conditions occur in the summer, when moisture from the crawl space travels through the floor and into the living space. Positioning a vapor barrier on the lower side of the sheathing prevents the moisture from penetrating the sheathing and raising its moisture content. Figure 6 shows the moisture content of plywood sheathing with and without a vapor barrier. Note that the moisture content of the floor sheathing with the vapor barrier varied from only 9 to 12 percent when a soil cover was in use and after it was removed. However, when no barrier was used, the moisture content of the sheathing rose to a 20-percent maximum with no soil cover and an 18-percent maximum with soil cover.

The homeowner can have his builder install a polyethylene vapor barrier over the joists before the floor sheathing is nailed to the joists. A second method,

and the one preferred, is to position batt-type insulation with integral vapor barrier next to the bottom of the sheathing. This approach not only protects the sheathing from moisture but also insulates the floor.

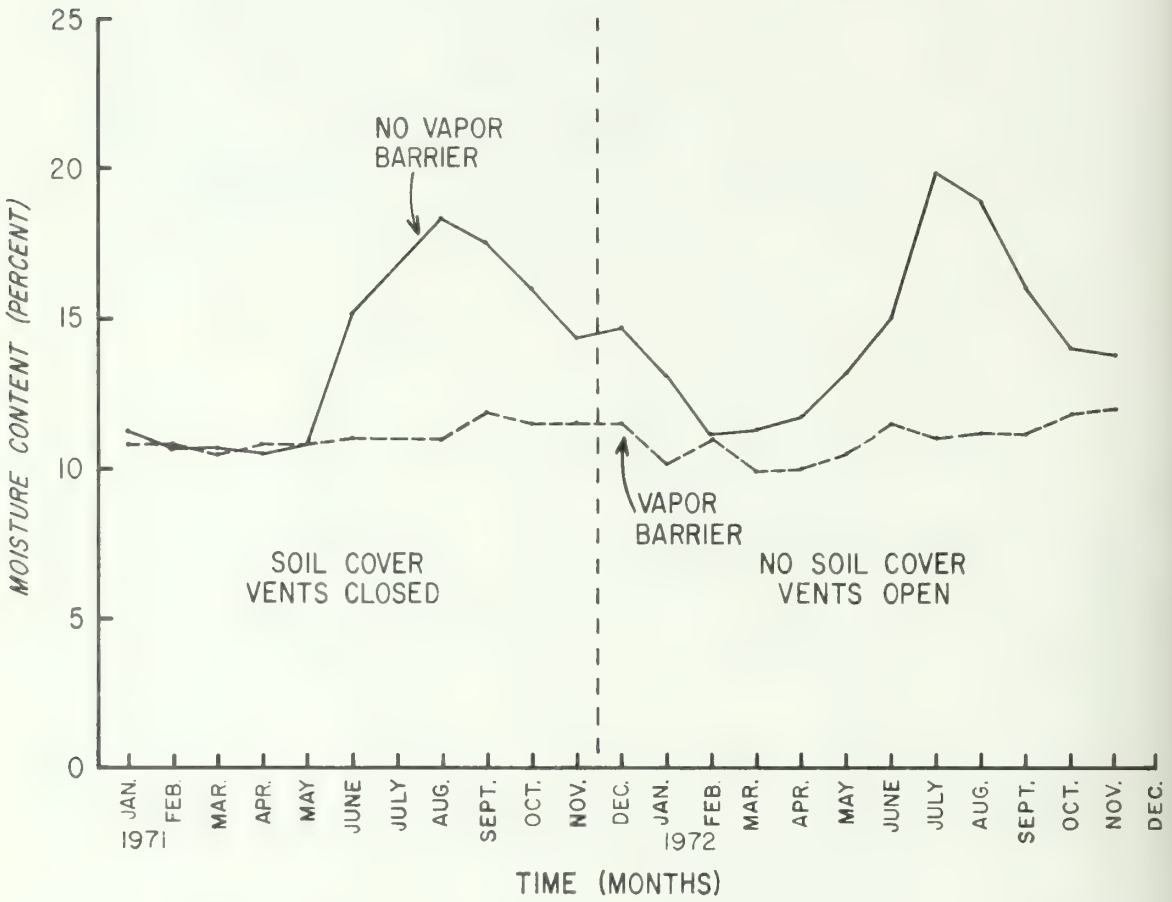

Figure 6.--A 2-year plot of the moisture content of floor sheathing with and without an underside vapor barrier (floor sections 1 and 5). During the first year, the soil was covered and vents were closed; during the second year, there was no soil cover and vents were open.

WHEN JOIST FLOORS ARE INSULATED, WILL THEIR MOISTURE CONTENT INCREASE ABOVE NORMAL?

Homeowners who wish to reduce their heating costs should insulate floors over crawl spaces. In mild climates, the insulation will not induce higher-than-normal moisture conditions in the floor. Figure 7 compares moisture conditions in a floor section that was insulated and one that was not; neither section contained a vapor barrier. The 2-year plot shows that moisture content of the sheathing for both floors was about the same with one exception. For a 10-month period beginning about a month after removal of the soil cover in November 1971, high humidity introduced into the crawl space resulted in a 2- to 3-percent difference in moisture content between the two floors.

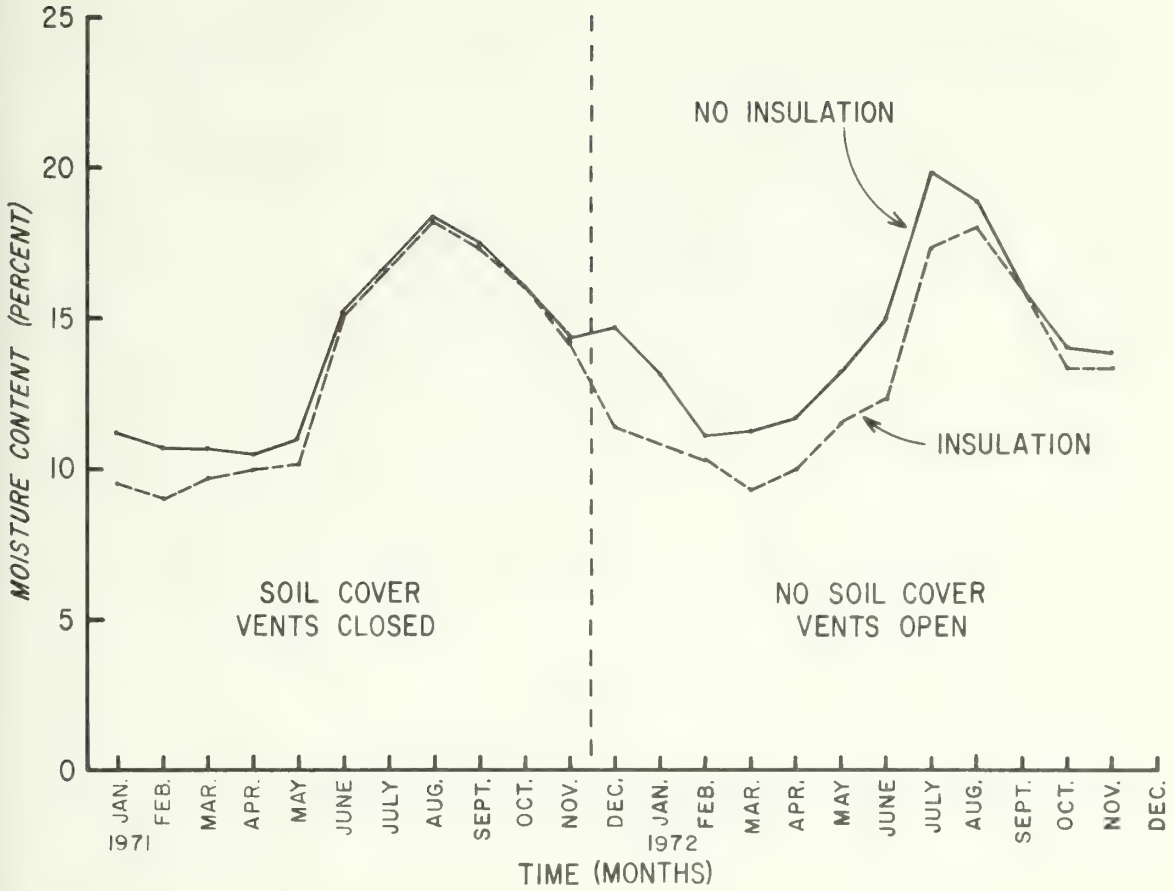

Figure 7.--A 2-year plot of the moisture content of floor sheathing with and without underfloor insulation (floor sections 1 and 2). During the first year, the soil was covered and vents were closed; during the second year, there was no soil cover and vents were open.

In general, the sheathing with the insulation was slightly less responsive to the high relative humidity because the circulation of the moist air near the underside was reduced. Note that the use of a soil cover with closed vents caused only a slightly lower peak moisture content (18 to 19 percent) in the sheathing than did no soil cover with vents open (20 to 21 percent).

WHAT ARE THE BENEFITS OF INSULATING FLOORS OVER CRAWL SPACES?

The most obvious benefit to the homeowner in insulating a floor is that it is warmer in winter. Figure 8 shows the temperatures of the air in the crawl space and of the sheathing in both insulated and uninsulated floors. During the winter, the insulated sheathing was approximately 10 degrees warmer than the uninsulated sheathing. However, the effect of the insulation on temperature of the floor sheathing disappeared rapidly with the approach of the warmer summer weather. The plot clearly shows that the temperatures of the air in the crawl space, the insulated sheathing, and the uninsulated sheathing converged during the summer months.

As the cool fall weather approached, the three temperatures again diverged. Thus, in mild climates floor insulation is of more benefit to the homeowner during winter than summer.

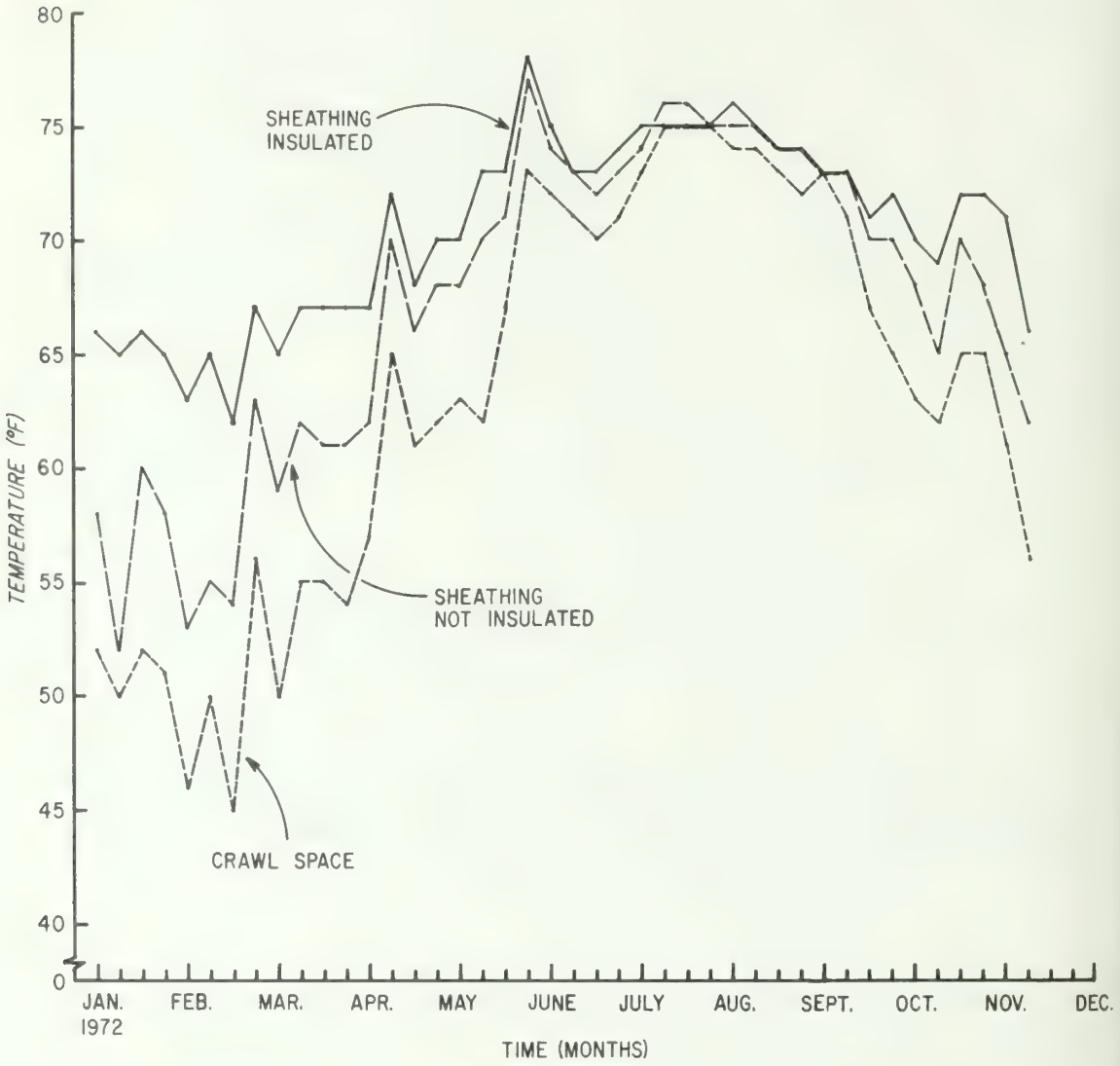

Figure 8.--A 12-month temperature plot of the air in the crawl space and of sheathing with and without underfloor insulation (floor sections 1 and 2).

HOW CAN A HOMEOWNER KEEP FLOOR JOISTS DRY?

In mild climates the moisture in the air of the crawl space tends to flow from the crawl space through the floor and into the living space. If a homeowner installs a vapor barrier on the bottom side of the joists, the joists will stay dry all year. Figure 9 shows a 2-year plot of moisture conditions in joists with and without an under-joist vapor barrier; both joists were in insulated floors. Moisture content of the joists with a vapor barrier remained at 10 to 12 percent over the 2-year study, whereas that of the joists without the vapor barrier varied from 10 to 21 percent. Although use of an under-joist vapor barrier keeps the floor dry, this method is not recommended where possible plumbing leaks would result in trapped moisture and severe decay hazards to the floor.

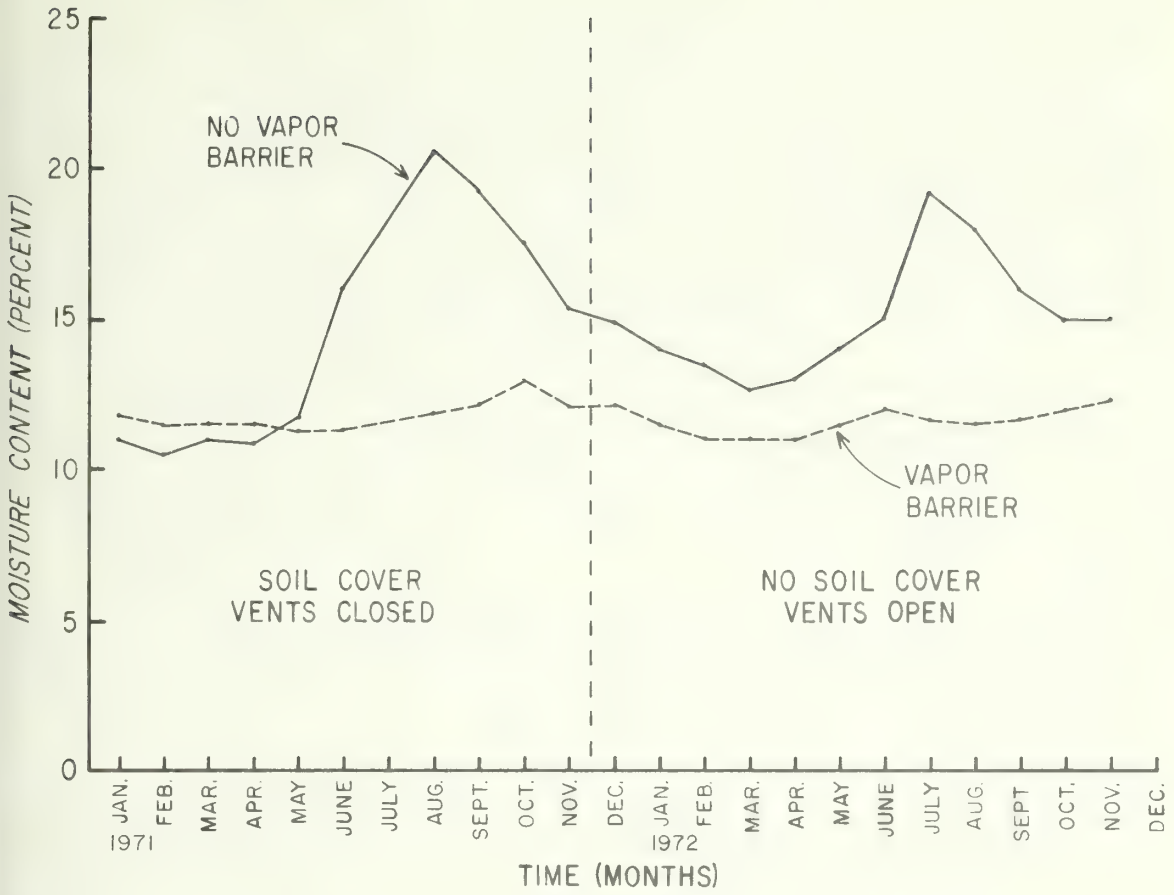

Figure 9.--A 2-year plot of the moisture content of insulated floor joists with and without an under-joist vapor barrier (floor sections 2 and 3). During the first year, the soil was covered and vents were closed; during the second year, there was no soil cover and vents were open.

If the homeowner desires to install batt-type insulation with an integral vapor barrier on the bottom, the lower portion of the joists will be exposed to the air in the crawl space and will vary in moisture content. However, the upper part of the joists should remain more uniformly dry during the year.

IF THE VAPOR BARRIER IS ABOVE THE FLOOR INSULATION, WILL THE FLOOR STAY DRY?

In mild climates, a homeowner can install the vapor barrier above the insulation and expect his floor sheathing to stay drier than if the vapor barrier were omitted. Figure 10 compares the moisture content of two insulated floor sections, one of which had a vapor barrier across the top of the joists, while the other did not. Notice that the sheathing in the floor section containing the vapor barrier remained much drier (8 to 12 percent moisture content) than the sheathing in the section without the vapor barrier (8 to 17 percent) during the 2-year study.

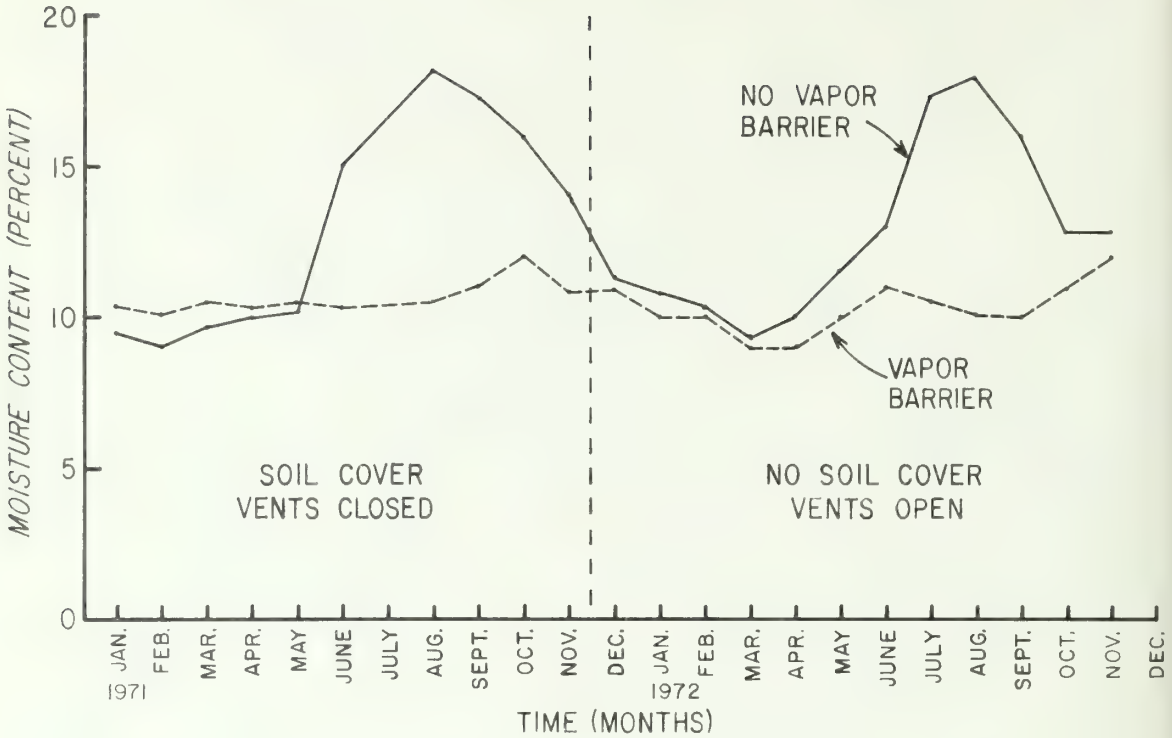

Figure 10.--A 2-year plot of the moisture content of insulated floor sheathing with and without an over-the-joist vapor barrier (floor sections 2 and 4). During the first year, the soil was covered and vents were closed; during the second year, there was no soil cover and vents were open.

HOW CAN HOMEOWNERS IN MILD CLIMATES MAXIMIZE THE BENEFITS OF FLOORS WITH CRAWL SPACES?

1. Homeowners can realize definite benefits in reduced heat losses and warmer floors by insulating between floor joists.

2. To provide a dry floor, homeowners should use a vapor barrier along with the insulation to reduce the movement of moisture from the crawl space into the wood floor. The vapor barrier should be positioned below the insulation to protect the joists except in floor areas where plumbing is installed. In those areas, homeowners should place the vapor barrier above the insulation, near the underside of the sheathing, in order to avoid trapping moisture from possible plumbing leaks and compounding decay hazards.

3. Homeowners building new homes should use a full soil cover in the crawl space. A soil cover permits the homeowner to conserve energy by closing the foundation vents and prevents moisture buildups in the crawl space which cause decay hazards in the floor.

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Duff, John E.
1978. Moisture content of a joist floor over a crawl space. U.S. Dep. Agric. For. Serv., Res. Pap. SE-189, 12 p. Southeast. For. Exp. Stn., Asheville, N. C.

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Moisture Content Changes in Wood Deck and Rail Components

by
Louis I. Gaby
and
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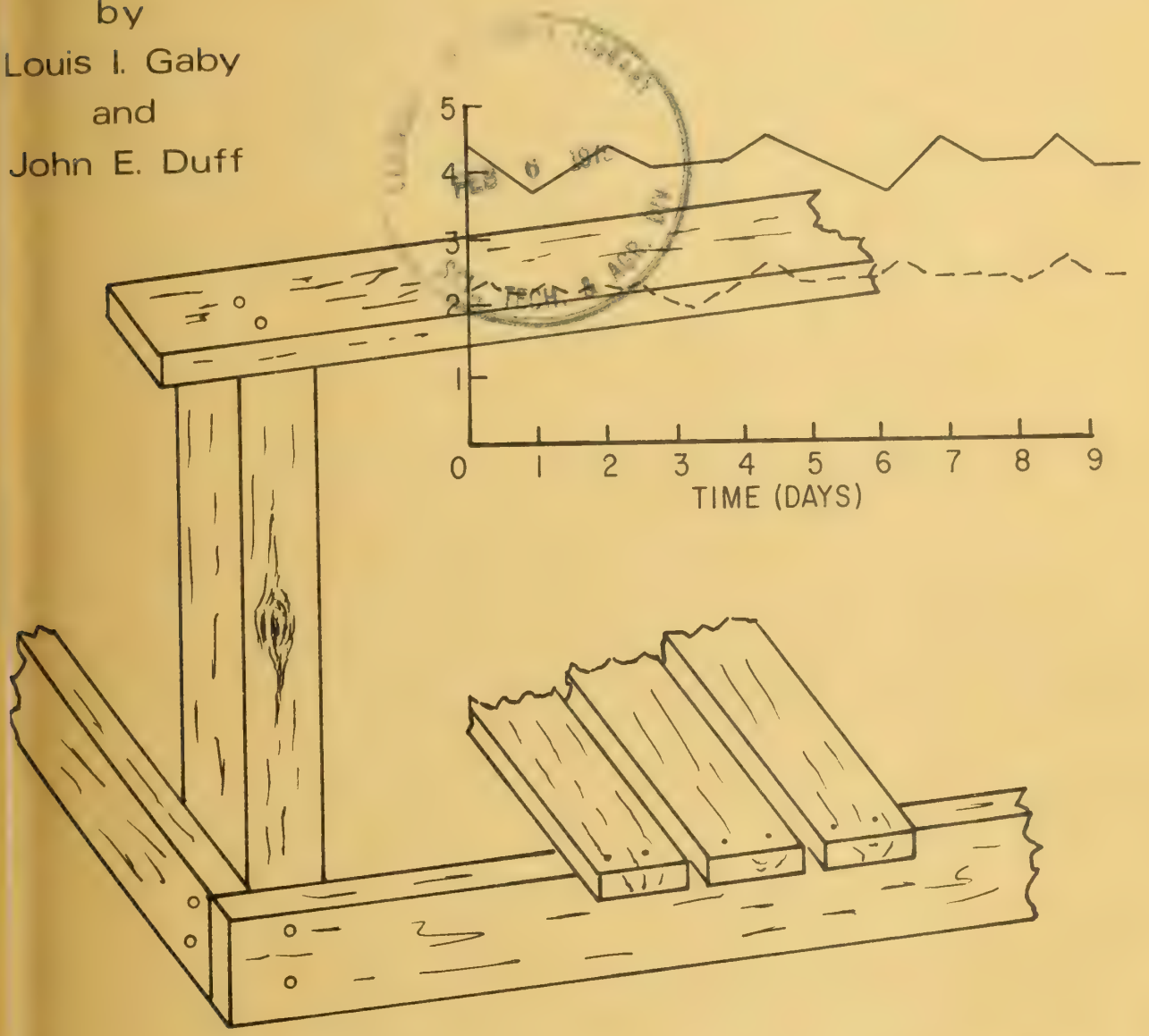

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July 1978

Southeastern Forest Experiment Station
Asheville, North Carolina

Moisture Content Changes in Wood Deck and Rail Components

by

Louis I. Gaby, Principal Wood Scientist

and

John E. Duff, Wood Scientist
Forestry Sciences Laboratory
Athens, Georgia

Abstract.--Exposure to frequent wetting and drying is a primary cause of wood deck deterioration, most of which occurs in untreated deck boards and in the lower parts of the railing where components are joined. Since rail components remain durable for many years when they are not subjected to an accumulation of water, their service life can be extended by assembling the components so that water is not trapped at end-grain surfaces.

KEYWORDS: Deterioration, exposure, wetting.

In the South the exterior wood decks of houses are often exposed to repeated wetting and drying (weathering), which leads to early deterioration. The various causes of deterioration--decay, warping, checking, shrinking, swelling, loss of strength, or combinations of these--are all related to large changes in the wood's moisture content.

The purpose of this study was to measure changes in the moisture content of wood decks exposed to natural weathering, and then to recommend how decks can be constructed to minimize deterioration from weathering. Specifically, the objectives of the study were to determine at what points water accumulates in the deck's structure after a rain, record the type and amount of deterioration at these points, identify construction methods which are related to deterioration, and recommend ways to construct better decks.

This information will be useful in any locality where deterioration is severe, where pressure-treated wood is not readily available, or where cost differences between treated and untreated wood are an important factor in deck construction.

EXPERIMENTAL DESIGN AND MEASUREMENTS

In order to determine and record moisture absorption and related deterioration typical of wood decks, an experimental deck was constructed around a small building near Athens, Georgia. This building housed an electronic automatic data collection unit (ADCU) with 127 connections to moisture content and temperature sensors.[1] The sensors could measure moisture content up to 30 percent and were inserted in pairs

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[1]Duff, John E. 1966. A probe for accurate determination of moisture content of wood products in use. U.S. Dep. Agric., For. Serv., Res. Note FPL-0142, 10 p. U.S. Dep. Agric., For. Serv., For. Prod. Lab., Madison, Wis.

(sets) at joint locations and at other points, as shown in figure 1. One sensor of each pair measured temperature; such readings were necessary for correcting the data on moisture content. Sensors were placed so as to avoid interference from nails used to assemble the deck. Most sensors were near end-grain surfaces because these surfaces gain and lose moisture more rapidly than others.

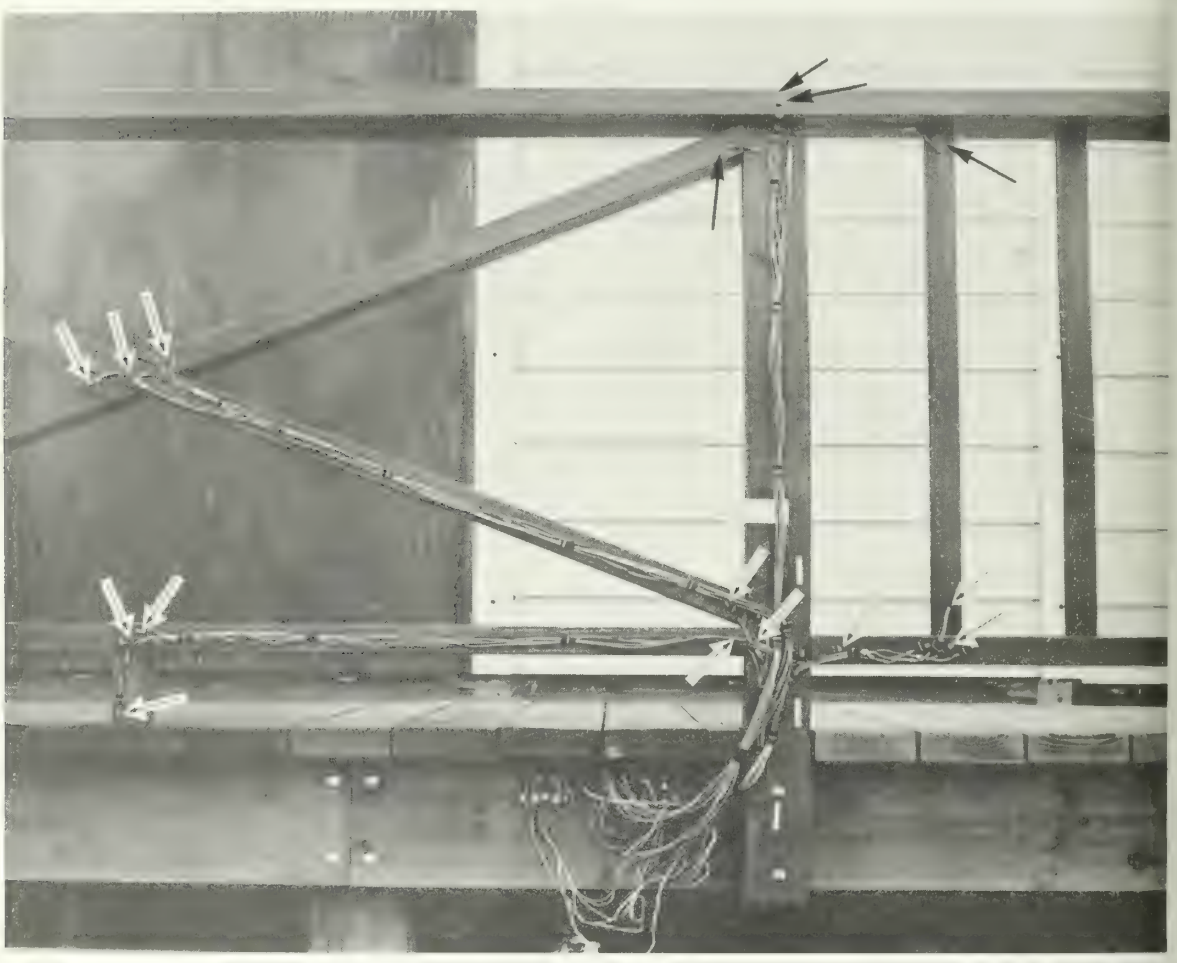

Figure 1.--Experimental deck with the "X" stretcher and baluster railings studied and the points (arrows) where moisture content was measured.

All sensors were scanned in sequence by the ADCU on wet and dry scanning modes. The wet mode was actuated by a rain sensor, and the amount of rain was then measured and recorded by an automatic weighing device. Moisture and temperature data were recorded by standard procedures. During rain, wet-mode scanning continued at hourly intervals and for a 6-hour period after the rain stopped. Dry scans were made every 6 hours during periods of no rain. All sensor data were automatically punched on paper tape and programmed through a computer, which plotted corrected moisture content over time for each sensor location. This information was collected for approximately 18 continuous months. In addition, the deck was inspected and amounts of wood distortion, mildew, decay, and nail problems were noted periodically for 7 year

Data on moisture content and deterioration were recorded primarily from the floor and railing components which consisted of untreated, kiln-dried southern pine; a few sensors were placed in the pine (treated with the preservative chromated coppe arsenate) that supported the framework and posts. The deck flooring consisted of

2 by 6 boards (5.08 cm by 15.24 cm), 54 inches (137.16 cm) long. On three sides of the house the deck floor was 6 inches (15.24 cm) or more above the ground; on the fourth side it was 1 inch (2.54 cm) or less above the soil. Sixteen sections of wood railings were made from untreated southern pine to surround the house on three sides. Sixteen sections of rails, eight of the "X" stretcher type and eight of the baluster type (fig. 1), were used for testing the types of joints most commonly employed in building decks; three of each type were wired with sensors.

After the first deck had been observed for 12 months, a second deck was constructed around an adjacent building in order to evaluate some design improvements. Conclusions drawn from examining the second deck were based only on observation; no sensors were placed in any of its components. Its design reduced a number of the water-trapping features observed in the original deck. The main improvements included (1) the elimination of parts sloped to joints, (2) the exposure, where possible, of ends of components for rapid drying, and (3) the elimination of parts placed with the wide face in a horizontal plane.

RESULTS AND DISCUSSION

Establishing a clear relationship between occurrences of rain and levels of moisture content in wood is difficult because no single rain duplicates another in terms of duration and amount. Because of the mass of data accumulated over 18 months, only a partial time segment is analyzed for illustration. The results presented here are for a 10-day period during the first year of intensive measurement. This particular period was chosen because it contained three rains of differing intensity and because the fluctuation in moisture content was typical of many other periods. It was preceded by 45 days with little or no rain, during which all parts of the deck and railing stabilized at moisture contents between 10 and 15 percent.

Three rains occurred during the period reported here: the first totaled 0.14 inch (0.36 cm) during a 5-hour period, the second totaled 0.79 inch (2.00 cm) in 10 hours, and the third totaled 1.64 inches (4.16 cm) in 11 hours. Their relative total volumes and elapsed times are shown by the vertical bars superimposed on the plots of changes in moisture content in the following sections. Correlations between amount and elapsed time of rain and moisture levels reached were not precisely defined because of equipment limitations.

AREAS OF SUSTAINED LEVELS OF HIGH MOISTURE

Four areas of the deck and railing retained high moisture contents (exceeding 25 percent) for extended periods, leading to early deterioration (fig. 2). These areas were: (1) the wide cap rail, (2) the horizontal rail at the lower end of vertical baluster rails, (3) the lower end of sloping rails used in stretcher-type railing, and (4) the deck boards. Wide cap rails and deck boards, both 6 inches (15.24 cm) wide in this deck, deteriorated more rapidly than other parts of the deck and railing. Because water does not readily run off flat surfaces, the retained water prevents the moisture content of the wood from changing quickly, whether in dry or rainy periods. Therefore, it is difficult to correlate moisture content and rain in these locations. Moisture contents are shown for the upper and lower layers of the wide cap rail in figure 3 and for checked and unchecked deck boards in figure 4.

Repeated wetting and drying cause large surface checks to develop during a year's exposure. As the checks enlarge, they can hold more water for longer periods and moisture penetrates more deeply. Within a few years these checks are ideal sites for decay fungi, and eventually the deterioration works its way from the top surfaces through to the underside of the boards. The development of surface checks

as sites for decay fungi has been reported by Scheffer and Verrall.[2] After 7 years, many sections of the rail cap, deck boards, and other horizontal members of the deck had completely deteriorated and collapsed of their own weight. Most of the deck boards were unsafe for foot traffic after 3 years of exposure, contained fruiting bodies (advanced decay), and were covered with various molds and mosses, which retain water.

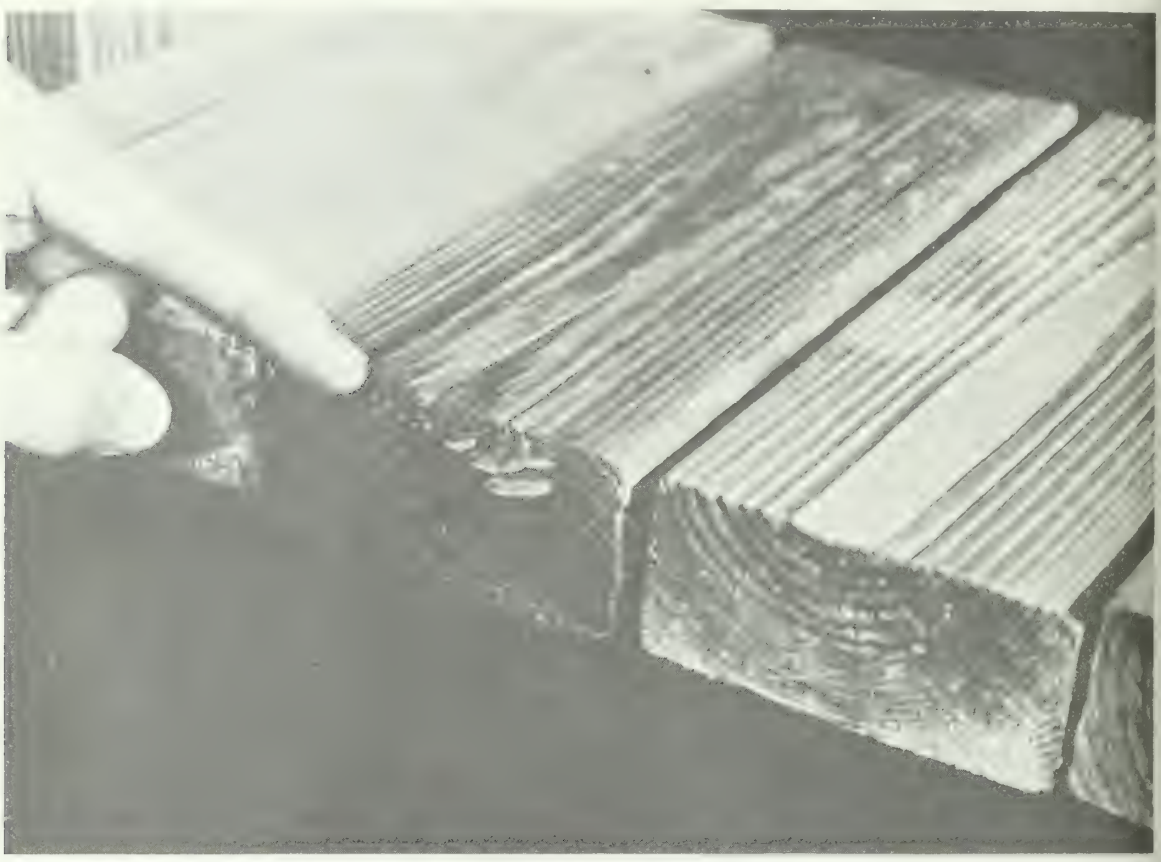

Figure 2.--Fruiting bodies indicate advanced decay in deck boards.

AREAS OF FLUCTUATING MOISTURE CONTENT

The areas that fluctuate most in moisture content are joints in railings where members form a water-trap. These particular joints also are usually in the more exposed, lower parts of the railing, where water accumulates. The joints usually include one member whose joint face is an end-grain surface. Nails used to hold the members together contribute to water absorption. One such joint, where two members meet at a post, is shown in figure 5. The moisture content in both the sloping and the horizontal members fluctuated widely in direct response to each rain. Diagonal joints such as this one have greater fluctuation in moisture than right-angle joints, which can be fitted more tightly, thus hindering the drying

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[2]Scheffer, T. C., and A. F. Verrall. 1965. Protecting wood in buildings from decay. Unpublished report. U.S. Dep. Agric., For. Serv., For. Prod. Lab., Madison, Wis. [In cooperation with the Bureau of Yards and Docks, Dep. of Navy, Washington, D.C.]

process. In this particular joint, greater moisture fluctuation occurred in the sloping member, but the horizontal member had a higher average moisture content.

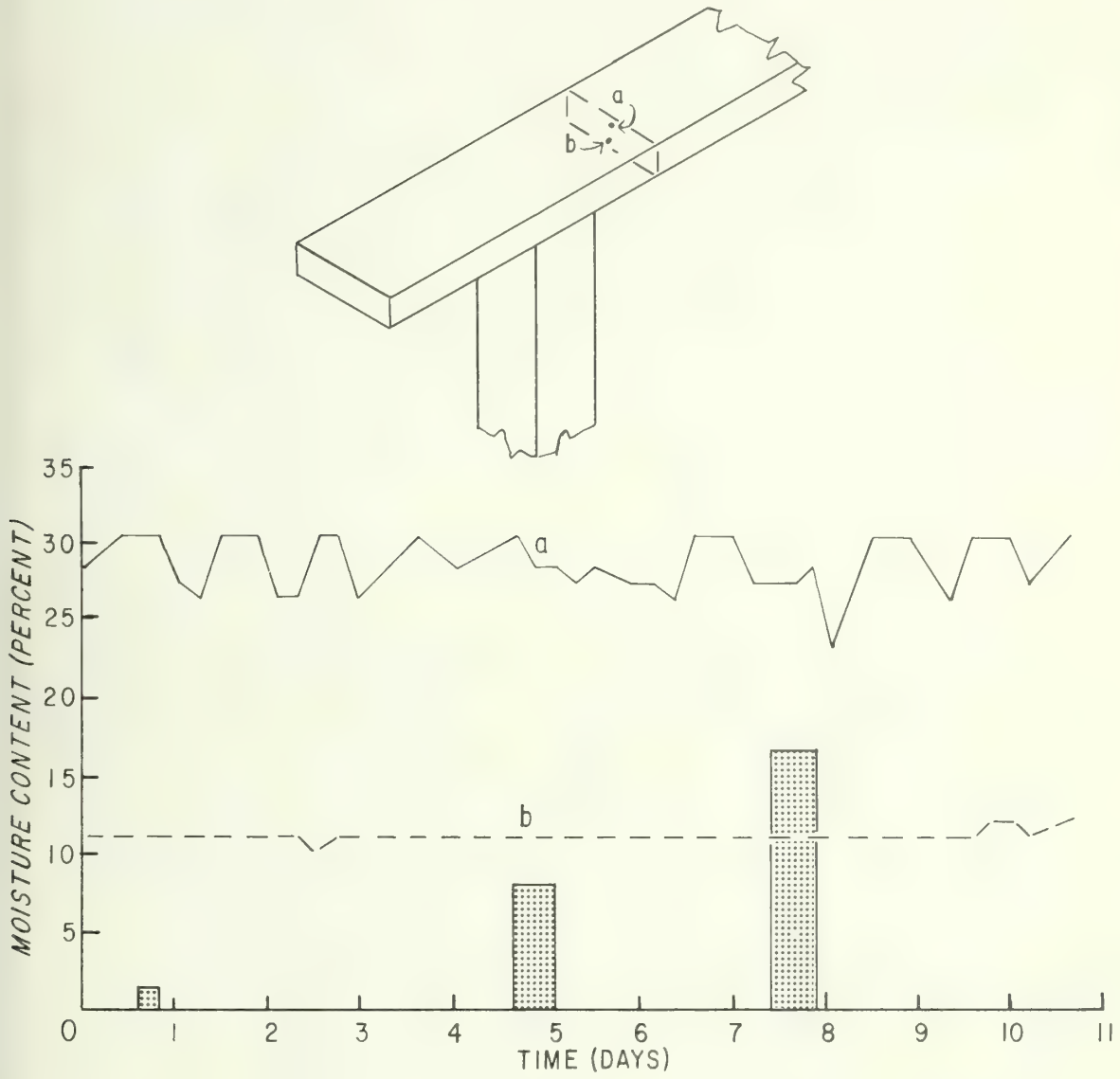

Figure 3.--Moisture content changes over a 10-day period in the upper (a) and lower (b) portions of a wide cap rail where surface checking has developed. Black bars show duration and relative volume of the three rains during the 10-day period.

Crossed members also respond quickly to rains. Figure 6 shows such a joint composed of three pieces in the middle stretcher railing, with one of the three pieces continuing through the joint. An increase in moisture content of 10 to 20 percent sometimes occurred in less than 3 hours in the short-nailed upper part of this joint (fig. 7). Although this upper part of the stretcher (plot a) reached high moisture levels, it did not hold water for long periods; the moisture content

dropped below 20 percent within 48 hours after rain had stopped. The short lower-side member (plot b) of the crossing responded less rapidly to rain than the upper-side member; however, its moisture content sometimes exceeded 25 percent before the wood began the same pattern of drying exhibited by the upper-side members. Underside ends of crossing members are somewhat protected from rain at the crossing point. A dark discoloration from mildew on the top surface is often an early indicator of moisture accumulation on the top surface. Symptoms of decay, as shown in figure 6, occur later.

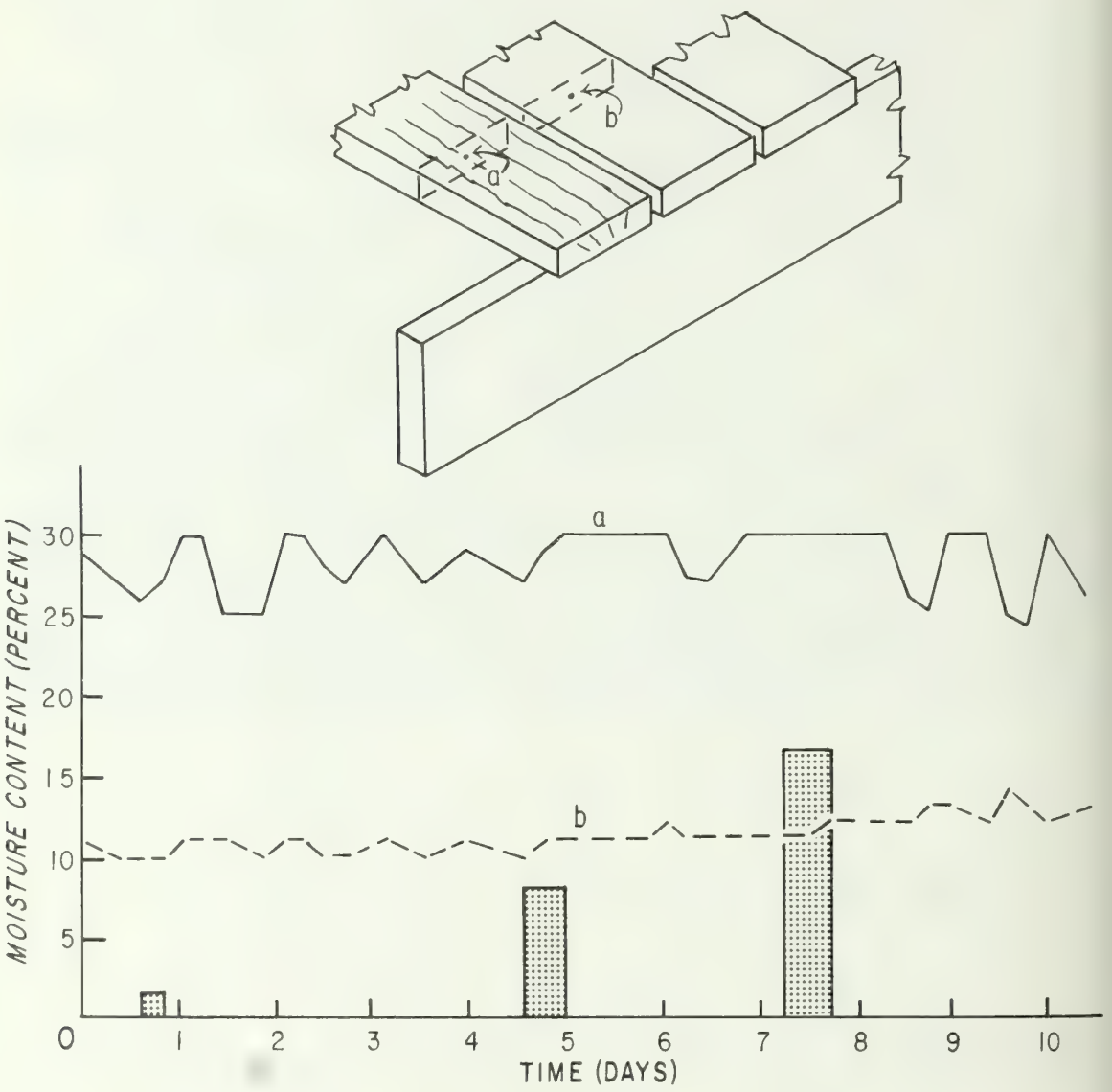

Figure 4.--Moisture content changes over a 10-day period in deck boards with deep surface checks (a) and those unchecked (b). Moisture probes were located at center of board, 1 foot from its end. Black bars show duration and relative volume of the three rains during the 10-day period.

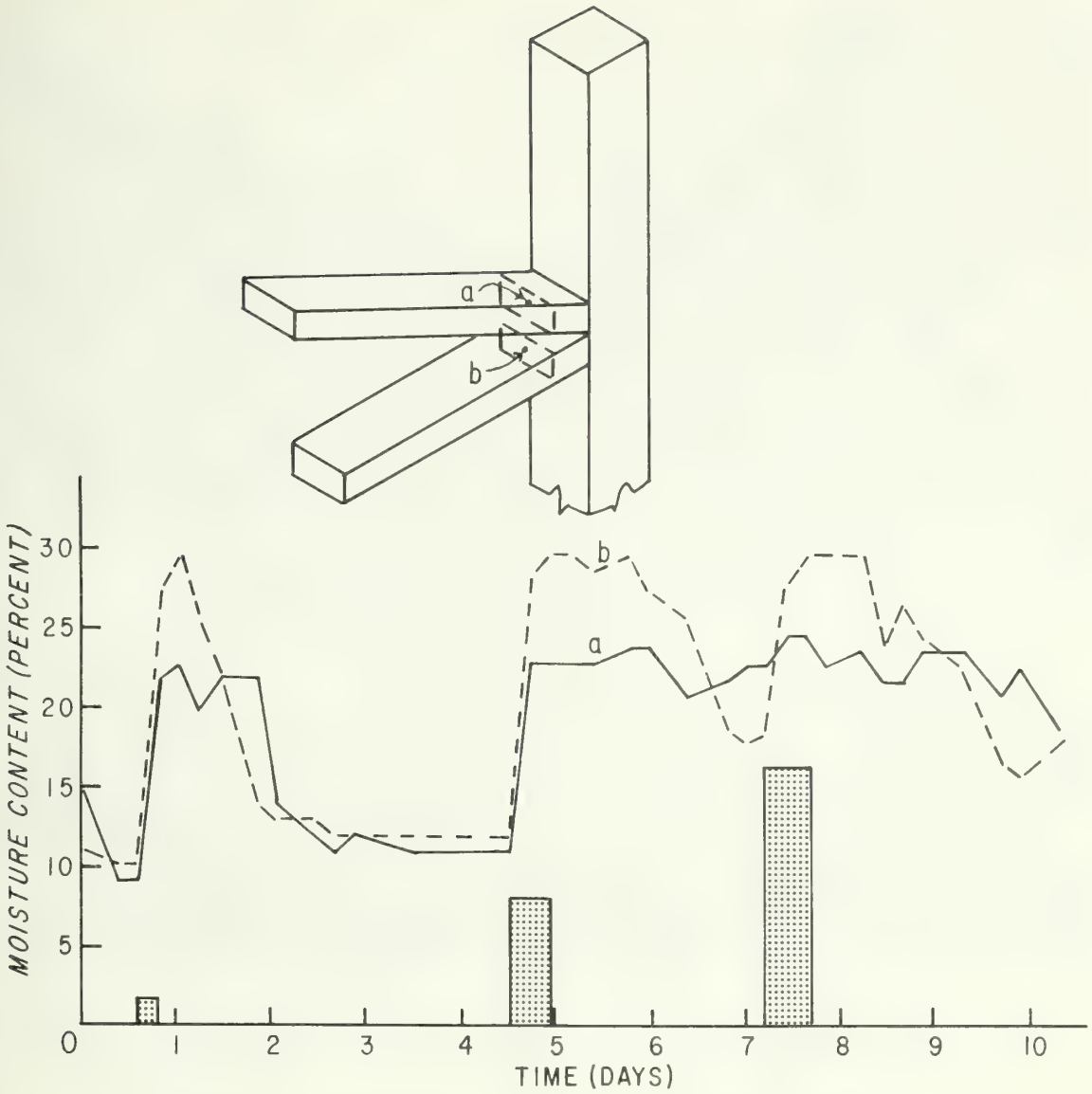

Figure 5.--Moisture content changes over a 10-day period at the ends of sloping (a) and horizontal (b) rail components that meet at a post. Black bars show duration and relative volume of the three rains during the 10-day period.

AREAS OF UNIFORMLY LOW MOISTURE CONTENT

Several locations where the deck member was protected from rain (or received little rain and dried out quickly) exhibited little or no change in moisture content over a period of years. The moisture content consistently remained at low levels (10 to 12 percent) in these locations because they were out of the path of rain flow. Such locations were usually between joints (away from end-grain surfaces) or under an overhanging member (fig. 8).

Figure 6.--Fruiting bodies located at a point of high moisture content in crossed members.

Changes in the moisture content of wood used in decks, and any resulting deterioration, are almost always due to rain. High relative humidity, which may occur daily during periods of no rain, is a lesser factor in causing high moisture content and deterioration. In many places, weather records show that during each 24-hour period there are several hours when the relative humidity is above 95 percent. In Georgia, these hours occur between midnight and sunrise during all seasons. Sustained levels of low moisture in parts of the test railing attest to the potential for reducing deterioration by designing and constructing decks without joints that trap water.

IMPROVED DECK RAILING DESIGN AND CONSTRUCTION

The second deck incorporated improved joining of deck rail members. Cap rails were constructed of 2 by 6 (5.08 cm by 15.24 cm) untreated pine boards but were placed so that the wide face was in the vertical plane, as seen in figure 9. End-grain faces at joints were eliminated by double posts wherever rails met, as shown in figure 10. Horizontal rails were attached to the sides of the posts instead of being nailed through the ends.

Another alternative to a horizontal cap rail is the vertical railing shown in figure 10. This railing is safe and eliminates nailing through ends of members. Note the gaps between cap rails and notches in the posts to prevent moisture accumulation in the joints. After 6 years there was no evidence of serious deterioration in the rail members of the second deck, as would have been indicated by discoloration (mildew), fruiting bodies (decay), or infected checks.

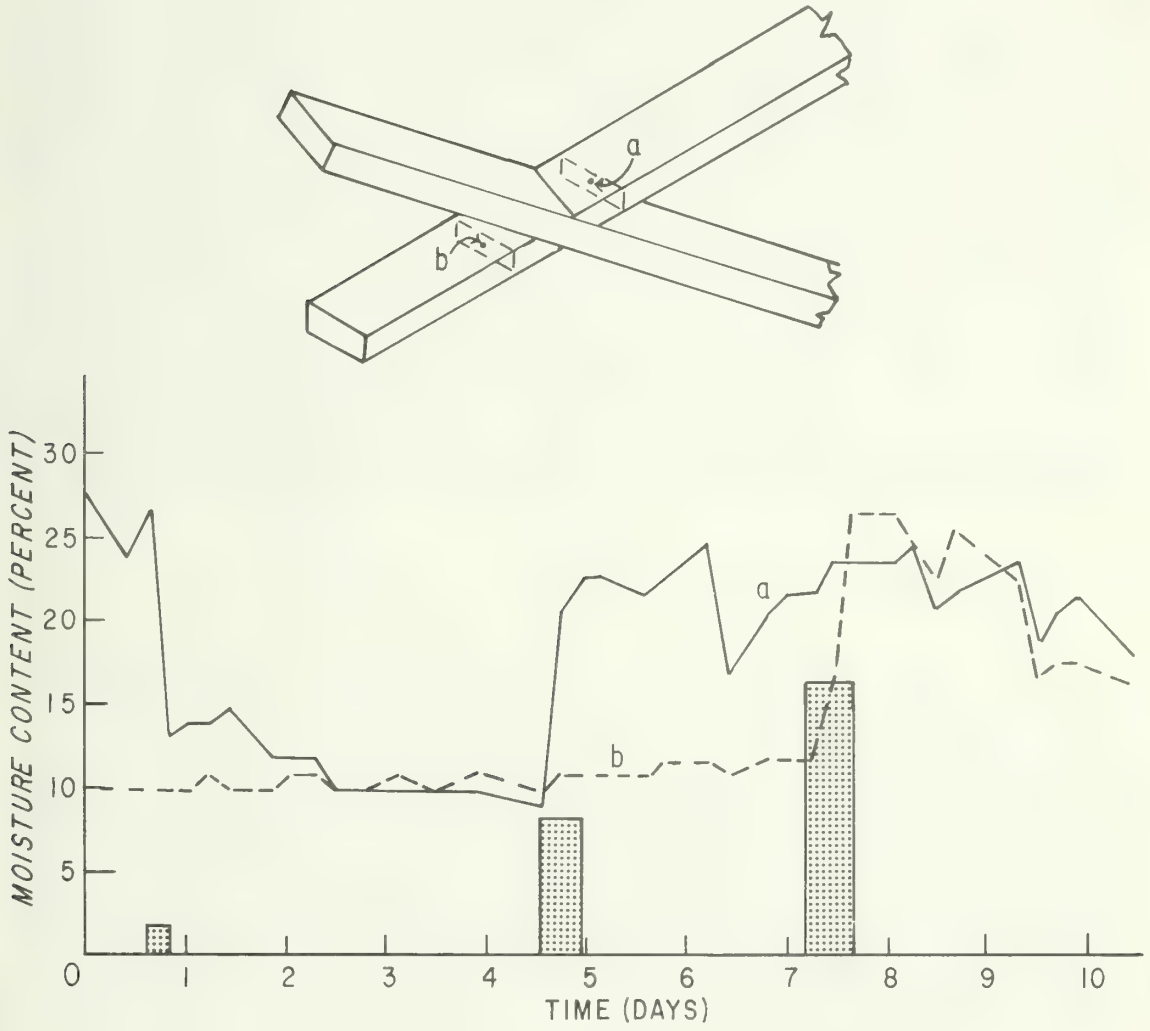

Figure 7.--Moisture content changes over a 10-day period in the ends of crossed rail members. Black bars show duration and relative volume of the three rains during the 10-day period.

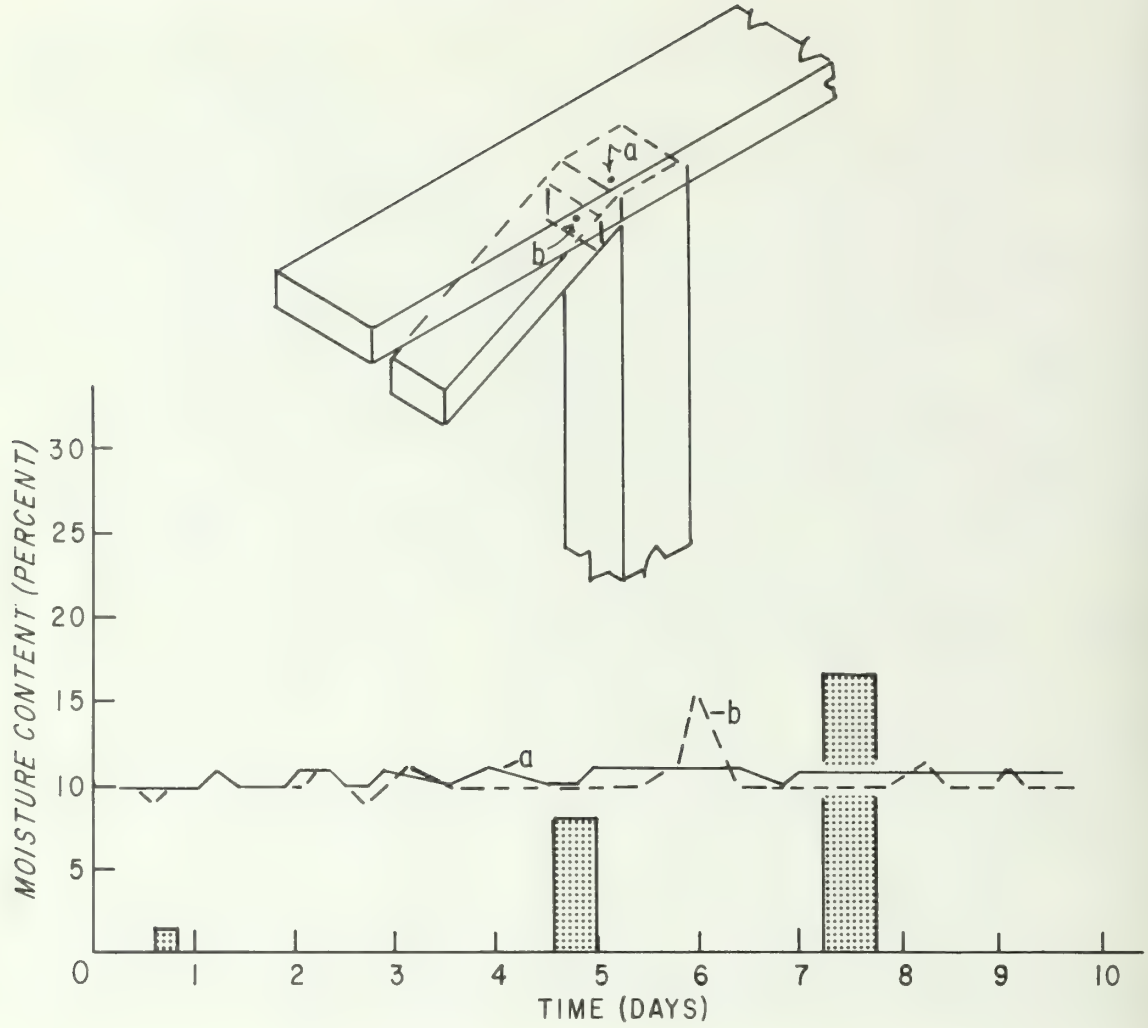

Figure 8.--Moisture content changes over a 10-day period at the ends of vertical (a) and sloped (b) rail components protected by a wide cap rail. Black bars show duration and relative volume of the three rains during the 10-day period.

Figure 9.--Cap rails placed so that the wide face is in the vertical plane to reduce large changes in moisture content from wetting.

Figure 10.--Horizontal railings attached to posts without creating joints that trap moisture.

CONCLUSIONS AND RECOMMENDATIONS

Wood decks deteriorate primarily from exposure to frequent wetting and drying. Most of the deterioration takes place in deck boards and in the lower parts of the railing where the ends of several members are joined. In wide deck boards and cap rails, deterioration is rapid after surface checks begin to widen. In railings, deterioration results from moisture absorption in the end grains of joints in the lower parts of railing components. As shown in this study, in areas where water does not accumulate, rail members remain durable even without treatment with wood preservatives. The service life of railings, whether treated or untreated, can be extended by assembling components so that water is not trapped at end-grain surfaces

Because deck boards are not a redesignable part of the deck, treatment with preservative or use of naturally durable wood are the main methods of controlling deterioration.

Gaby, Louis I., and John E. Duff
1978. Moisture content changes in wood deck and rail components. U. S. Dep. Agric. For. Serv., Res. Pap. SE-190, 12 p. Southeast. For. Exp. Stn., Asheville, N. C.

Exposure to frequent wetting and drying is a primary cause of wood deck deterioration, most of which occurs in untreated deck boards and in the lower parts of the railing where components are joined. Since rail components remain durable for many years when they are not subjected to an accumulation of water, their service life can be extended by assembling the components so that water is not trapped at end-grain surfaces.

KEYWORDS: Deterioration, exposure, wetting.

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